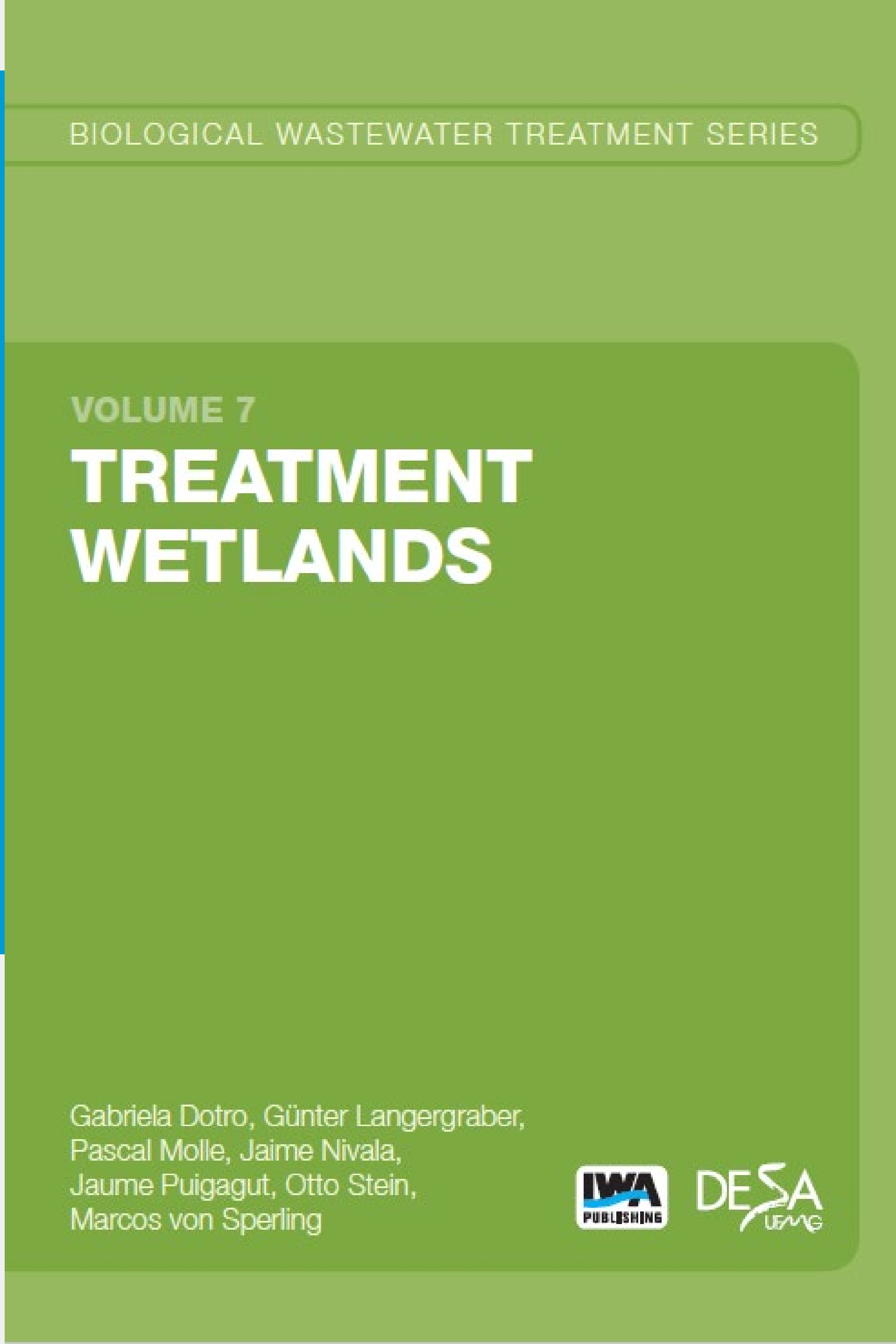
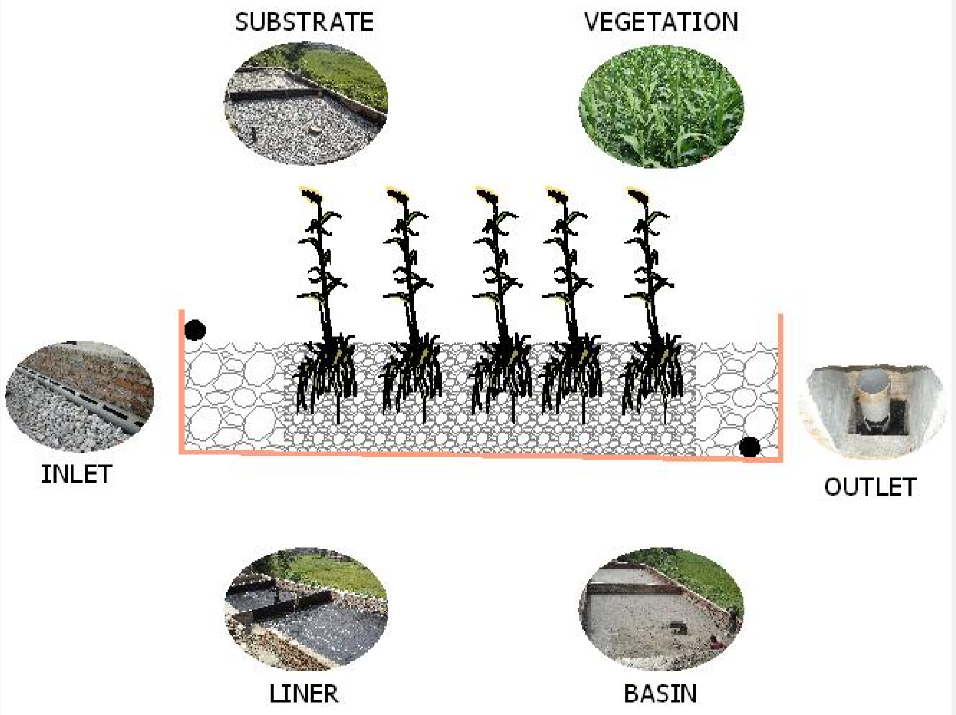
Constructed Wetland

Shirish Singh



What is a Constructed Wetland?

- Engineered system designed to mimic/optimize processes found in natural wetland ecosystems;
- System that utilize wetland plants, soils and their associated microorganisms to remove contaminants from wastewater, as well as other sources of contamination.
- Biological wastewater treatment technology;

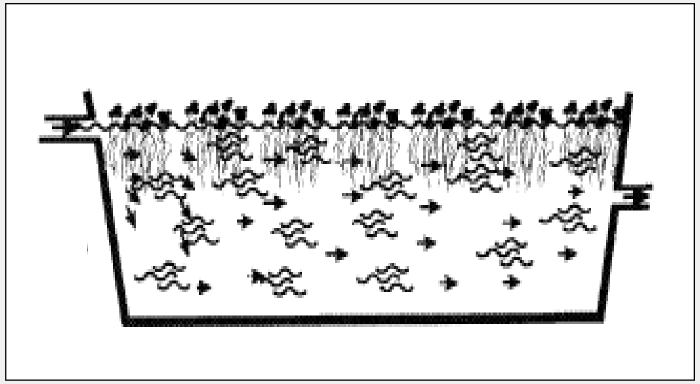


Classification/Types of CW

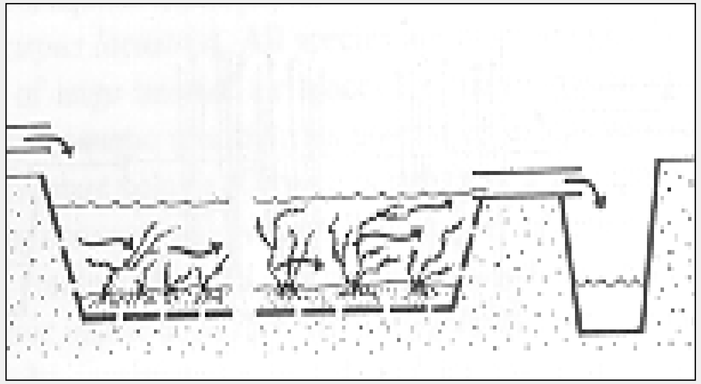
- Life form of the dominating macrophytes
- Flow pattern in the wetland systems
- Type of configurations of the wetland cells (hybrid systems, one-stage, multi-stage systems),
- Type of wastewater to be treated (industrial, municipal, grey water etc.),
- Treatment level of wastewater (primary, secondary or tertiary),
- Type of substrate (gravel, soil, sand, etc.), and
- Type of loading (continuous or intermittent loading).

Based on dominant macrophyte

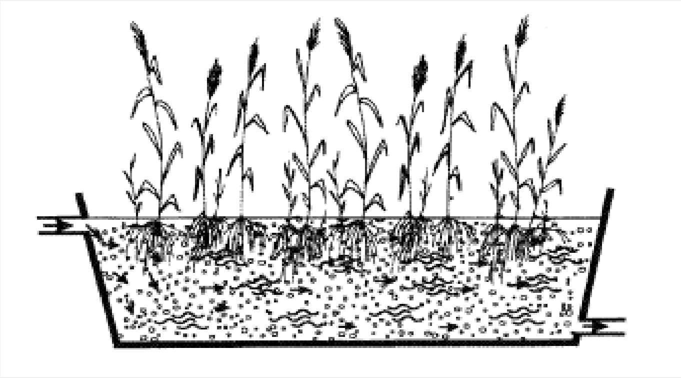
Free floating macrophyte-based system



Submerged macrophyte-based system

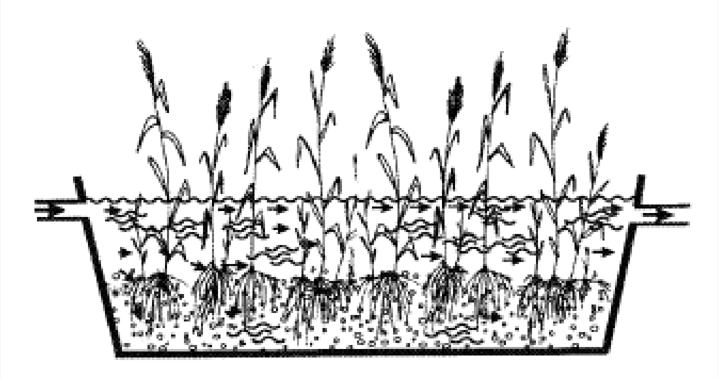


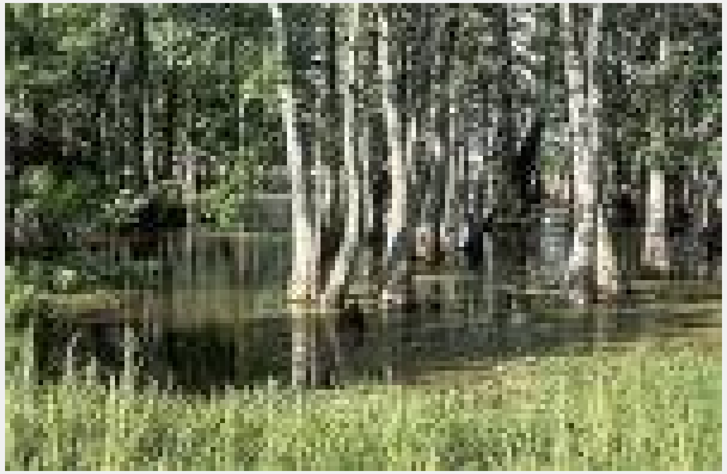
Emergent macrophyte-based system



Based on flow pattern

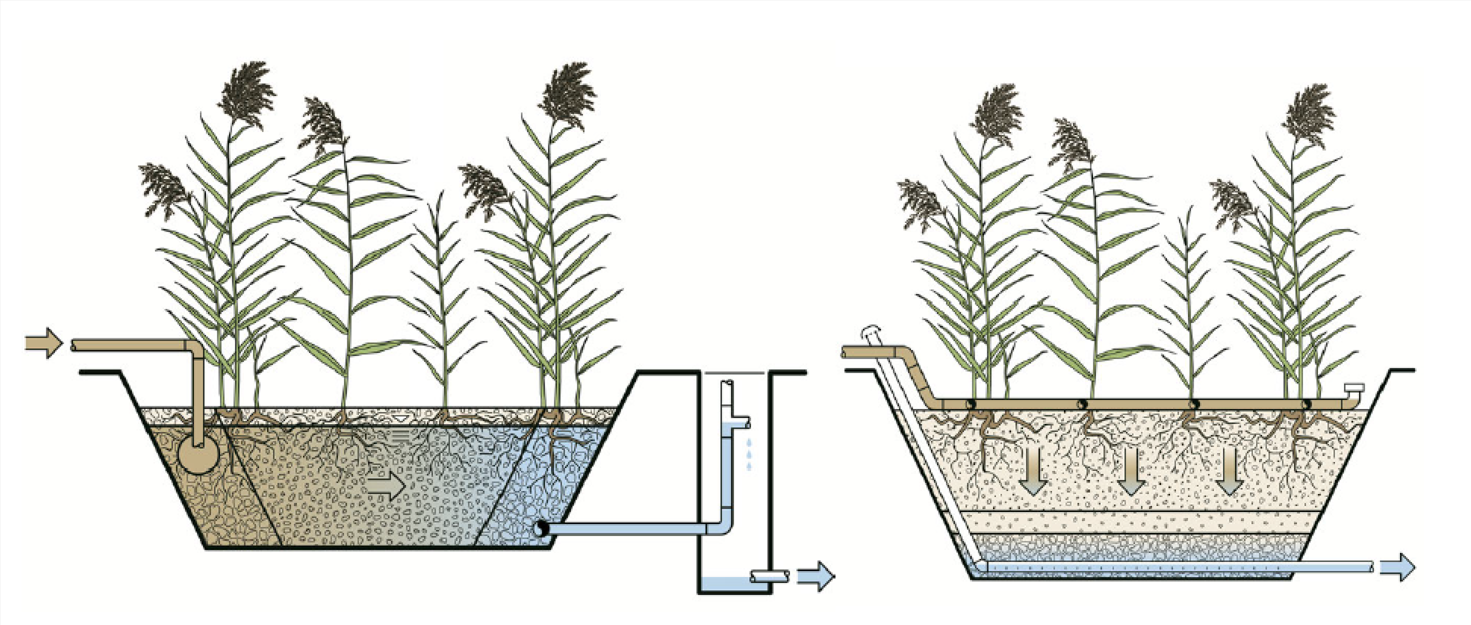
Free Water Surface (FWS) wetlands – majority of water flows above the soil surface





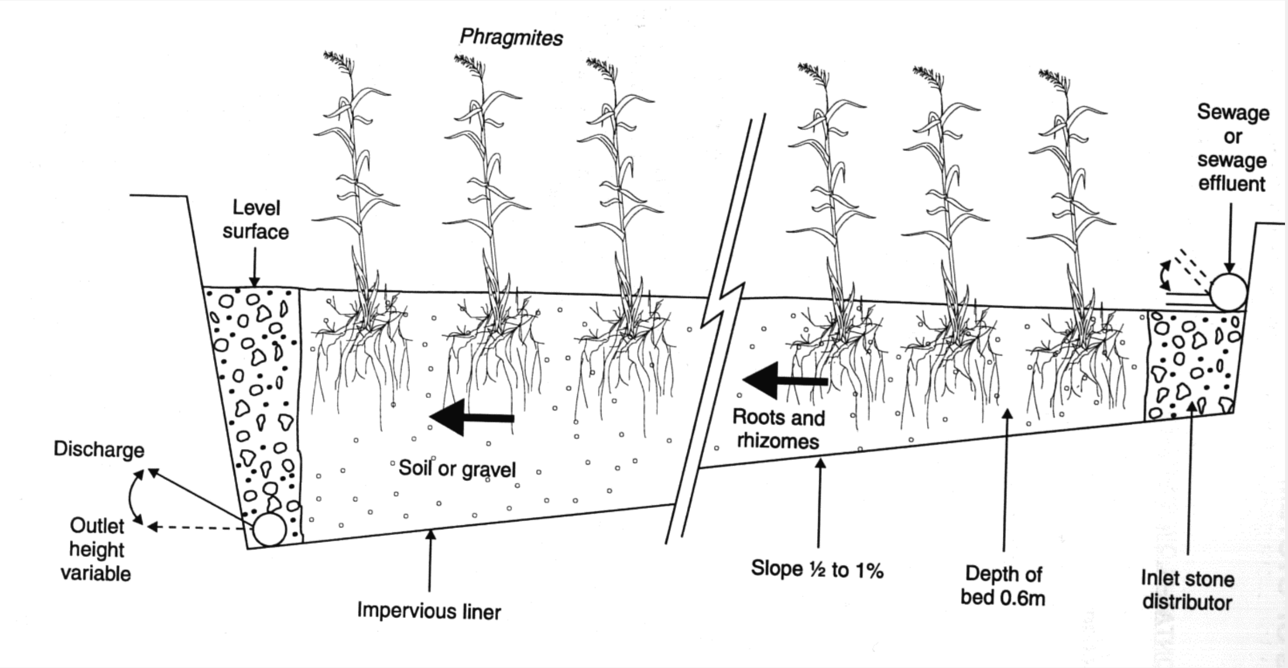
Sub Surface Flow (SSF) wetlands – flow is directed through the rooting media with no overland flow

- Horizontal Flow (HF)
- Vertical Flow (VF)



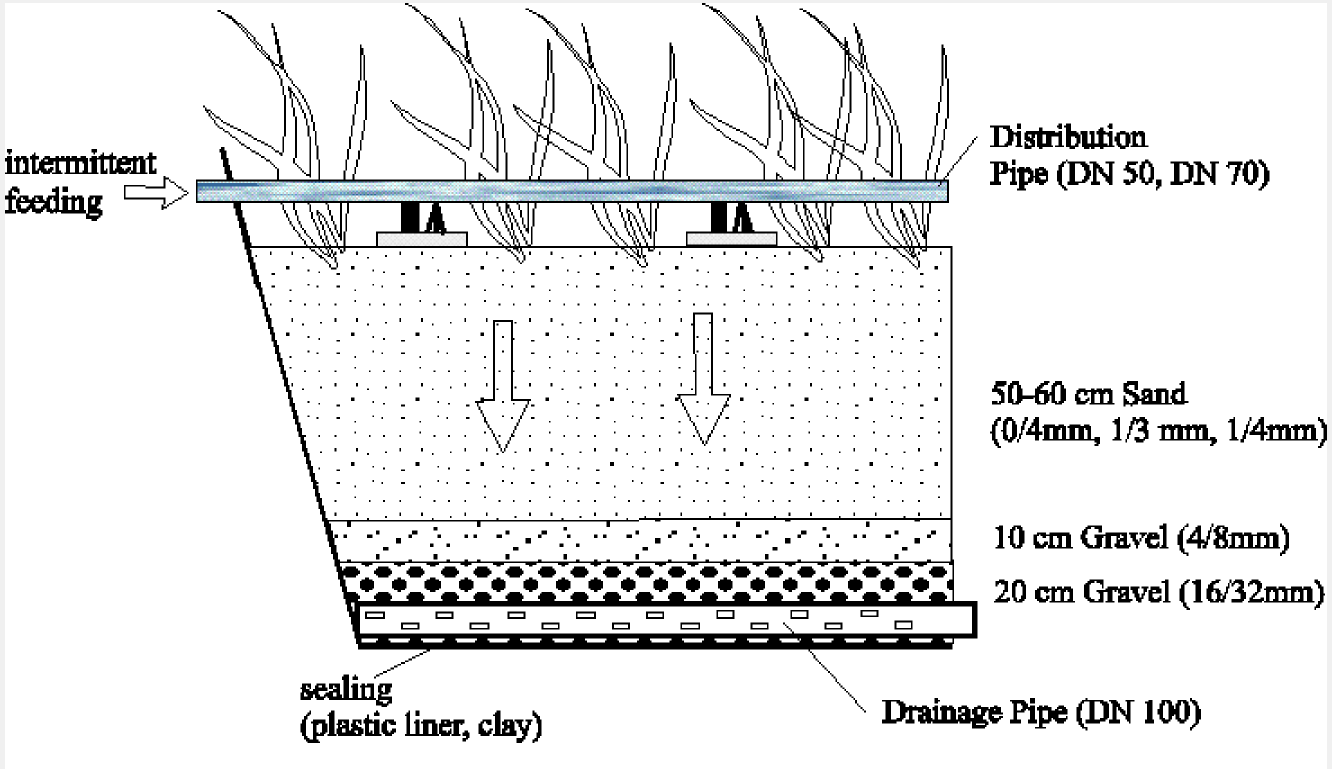
Horizontal Flow

- Wastewater flows horizontally through a sand or gravel based filter whereby the water level is kept below the surface.
- Due to the water-saturated condition mainly anaerobic degradation processes occur.
- Effective primary treatment is required to remove particulate matter to prevent clogging of the filter.
- Emergent plants (macrophytes) are used.
- Are used for secondary or tertiary treatment.



Vertical Flow

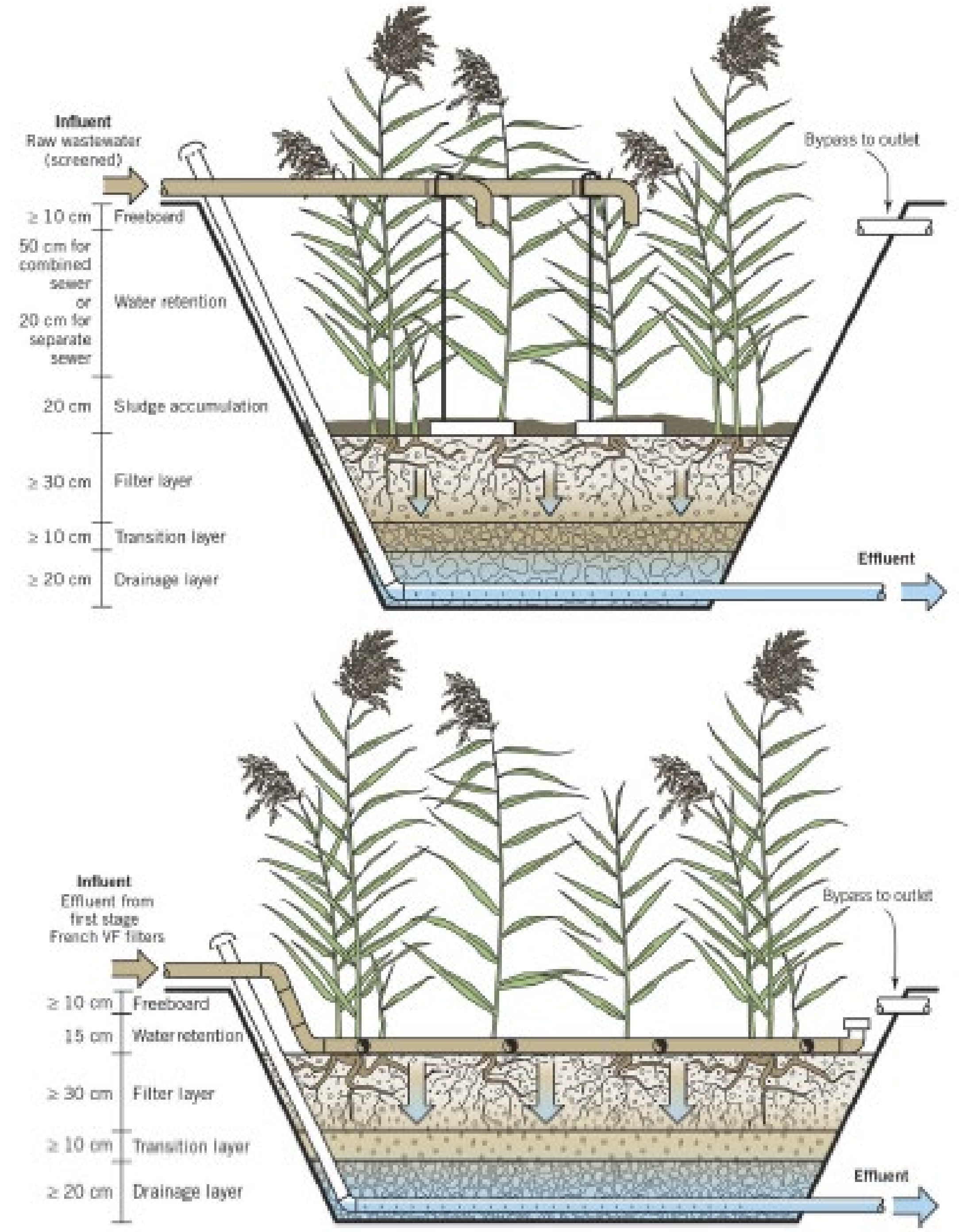
- Wastewater is intermittently loaded on the surface of the filter and percolates vertically through the filter.
- Between two loadings air re-enters the pores and aerates the filter so that mainly aerobic degradation processes occur.
- Effective primary treatment is required to remove particulate matter to prevent clogging of the filter.
- Emergent macrophytes are used.



Typical Arrangement for a Vertical Flow Bed

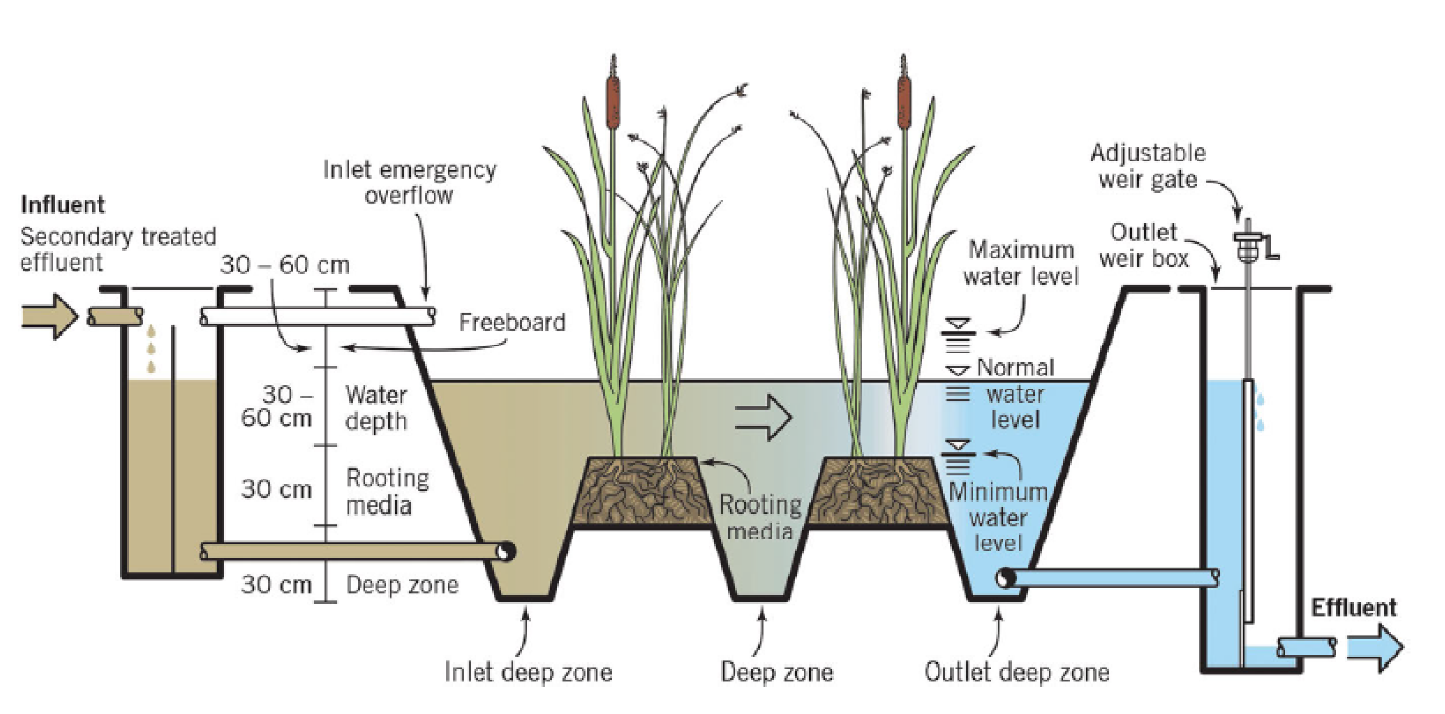
French Vertical Flow

- Are VF wetlands for treating screened wastewater.
- Two stages of wetlands operate in series and in parallel.
- Provide integrated sludge and wastewater treatment in a single step.
- No primary treatment unit is required.



Free Water Surface (FWS)

- Resemble natural wetlands in appearance.
- Require large surface area, are generally lightly loaded.
- Various plant genus can be used: a) emergent (b) submerged (c) floating: *Eichornia* (water hyacinth), *Lemna* (duckweed).
- Are mainly used for tertiary treatment.



Wetland plants

Typha or cattail

Phragmites or reed

Scirpus or bulrush

Wetland plants (flowering)

Canna spp.

Iris spp.

Heliconia spp.

Typical removal efficiencies

Parameters	HF	VF [a]	French VF	FWS
Treatment step (main application)	Secondary	Secondary	Combined primary and secondary	Tertiary
Total Suspended Solids	> 80%	> 90%	> 90%	> 80%
Organic matter (measured as oxygen demand)	> 80%	> 90%	> 90%	> 80%
Ammonia nitrogen	20 – 30%	> 90%	> 90%	> 80%
Total nitrogen	30 – 50%	< 20%	< 20%	30 – 50%
Total phosphorus (long term)	10 – 20%	10 – 20%	10 – 20%	10 – 20%
Coliforms	2 $\log_{10}$	2 – 4 $\log_{10}$	1 – 3 $\log_{10}$	1 $\log_{10}$

[a] Single-stage VF bed, main layer of sand (grain size 0.06 – 4 mm)

Land area requirement

Treatment technology	Treatment area requirement (m²/PE)
Facultative pond [a]	2.0 – 6.0
Anaerobic + facultative pond [a]	1.2 – 3.0
UASB reactor [a]	0.03 – 0.10
Activated sludge, SBR [a]	0.12 – 0.30
Trickling filter [a]	0.15 – 0.40
HF wetlands [b]	3.0 – 10.0
VF wetlands [b]	1.2 – 5.0
French VF wetlands [c]	2.0 – 2.5

[a] (von Sperling, 2007a)
[b] for warm (Hoffmann *et al.*, 2011) and temperate climates (Kadlec and Wallace, 2009)
[c] for temperate climates (Molle *et al.*, 2005)

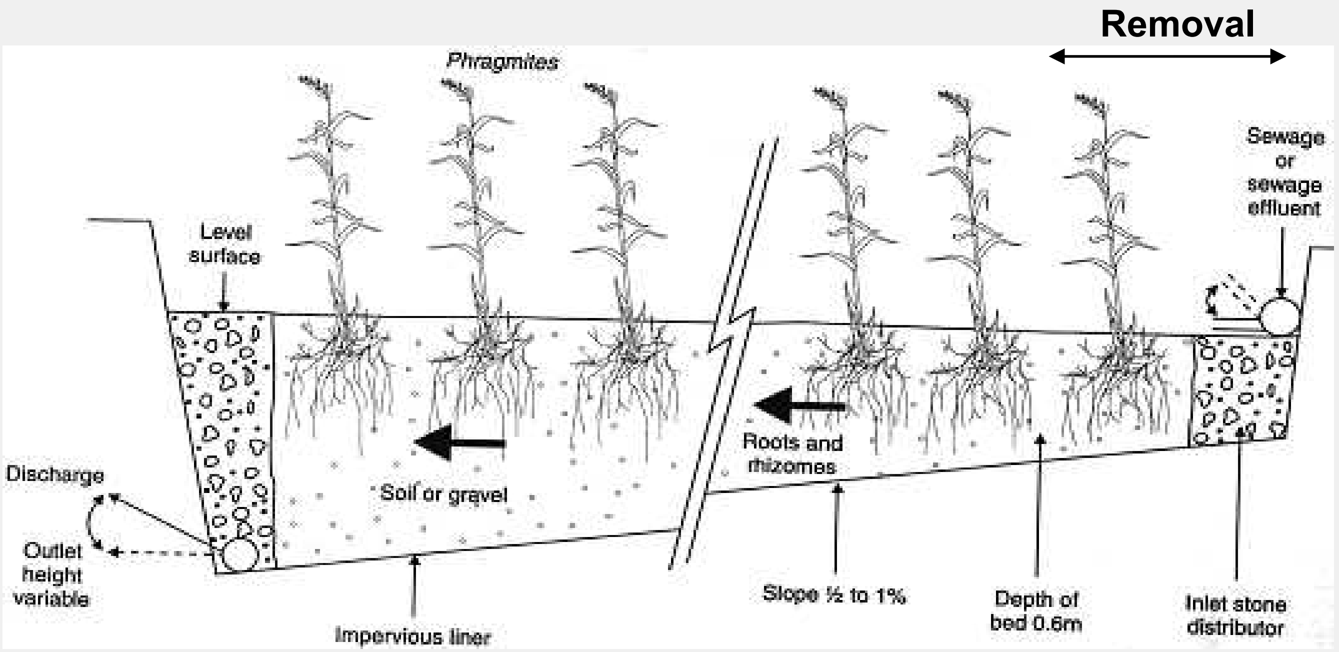
Pollutant and Pathogen removal mechanism

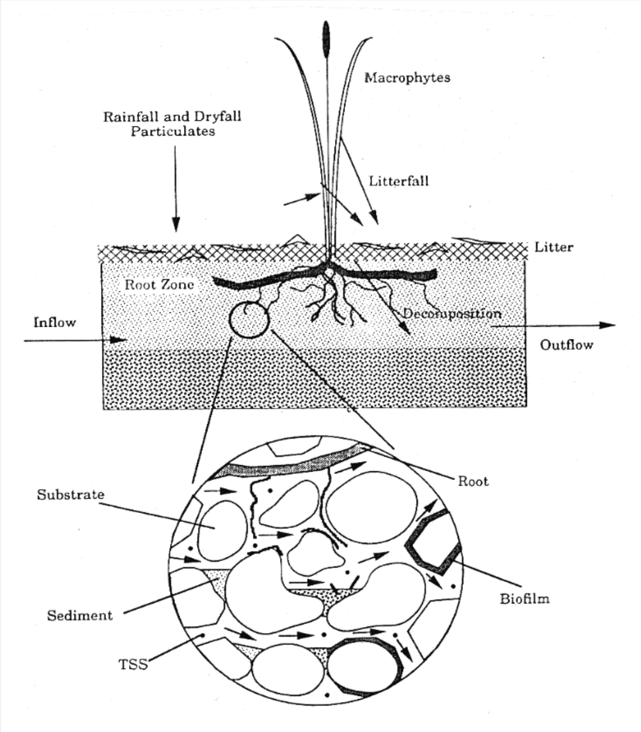
Parameter	Main removal mechanisms
Suspended solids	Sedimentation, filtration
Organic matter	Sedimentation and filtration for the removal of particulate organic matter, biological degradation (aerobic and/or anaerobic) for the removal of dissolved organic matter
Nitrogen	Ammonification and subsequent nitrification and denitrification, plant uptake and export through biomass harvesting
Phosphorus	Adsorption-precipitation reactions driven by filter media properties, plant uptake and export through biomass harvesting
Pathogens	Sedimentation, filtration, natural die-off, predation (carried out by protozoa and metazoa)

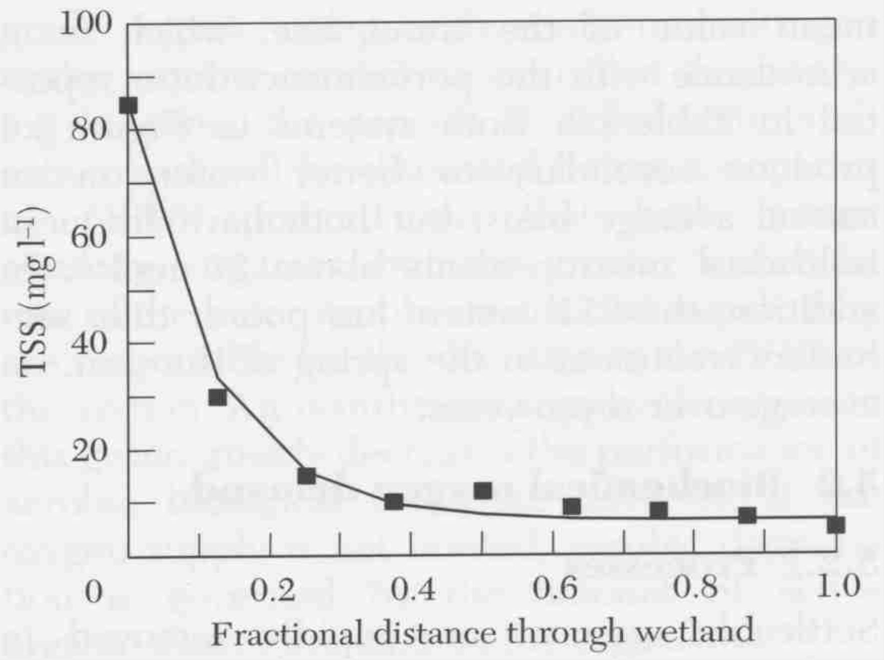
Suspended Solids

- Sedimentation
- Filtration

Most of the suspended solids are eliminated at the inlet end of the bed.







Organic matter

- Particulate organic matter
  - Filtration
  - Sedimentation

- Soluble organic matter (chemical reaction – electrons are transferred from organic matter (electron acceptor) to a compound (electron donor) releasing energy for cell growth
  - Aerobic microbial respiration (oxygen is electron acceptor) $CO_2 \uparrow$
  - Denitrification (nitrate and nitrite as electron acceptor) $N_2 + CO_2 \uparrow$
  - Sulphate reduction (sulphate as electron acceptor) $S + CO_2 \uparrow$
  - Methanogenesis (organic matter is simultaneously electron acceptor and donor) $CH_4 + CO_2 \uparrow$

Nitrogen

- Primary and Secondary - Organic N and ammonium (NH_4-N) + nitrate (in tertiary systems)
  - Ammonification (organic N to ammonium)
  - Nitrification (oxidation of ammonium to nitrate)
  - Denitrification (nitrate to nitrogen gas)
  - Sorption (ammonium as cation sorbed onto media particles; zeolite)
  - Plant uptake (if plants are not harvested, no nitrogen removal)

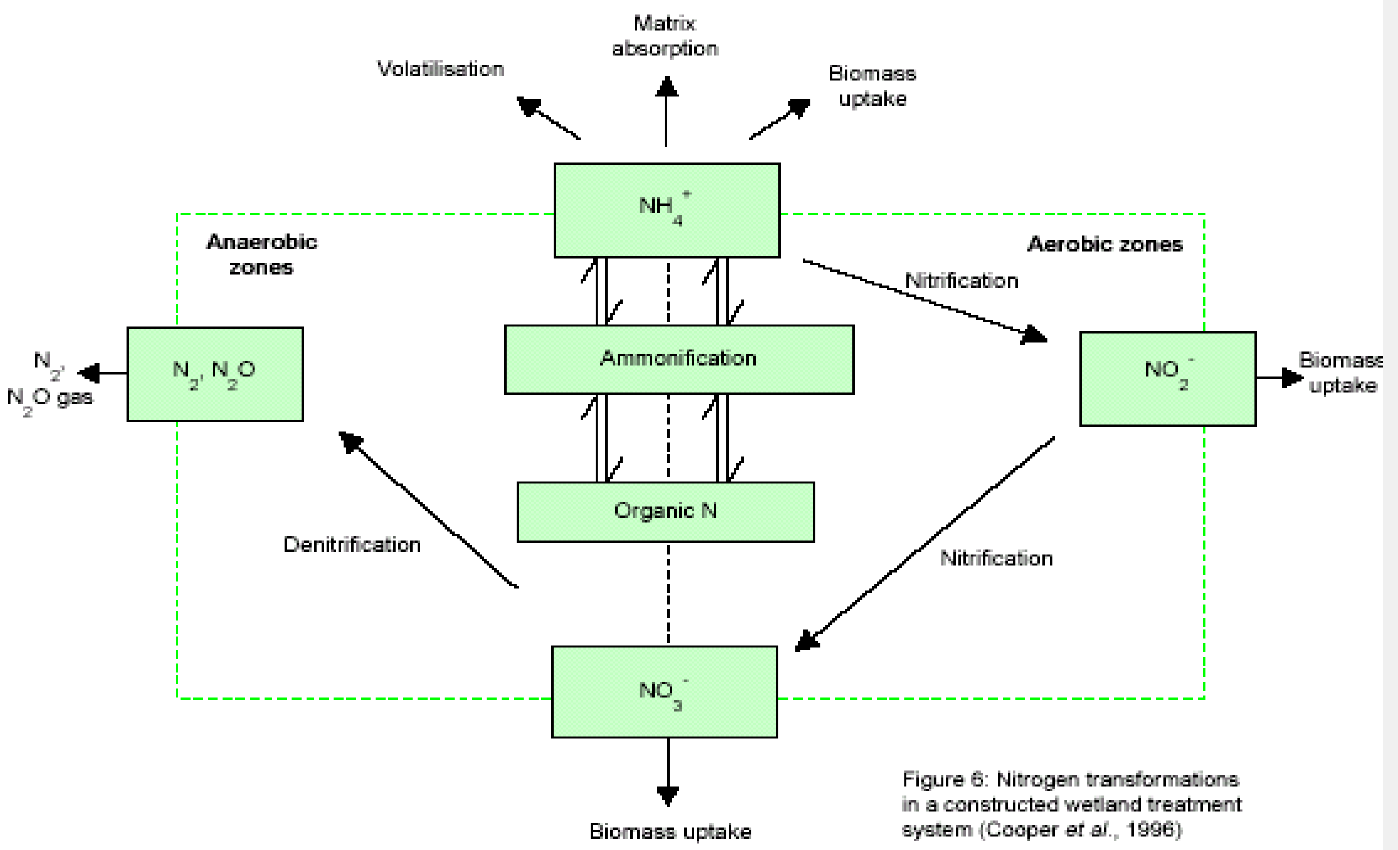
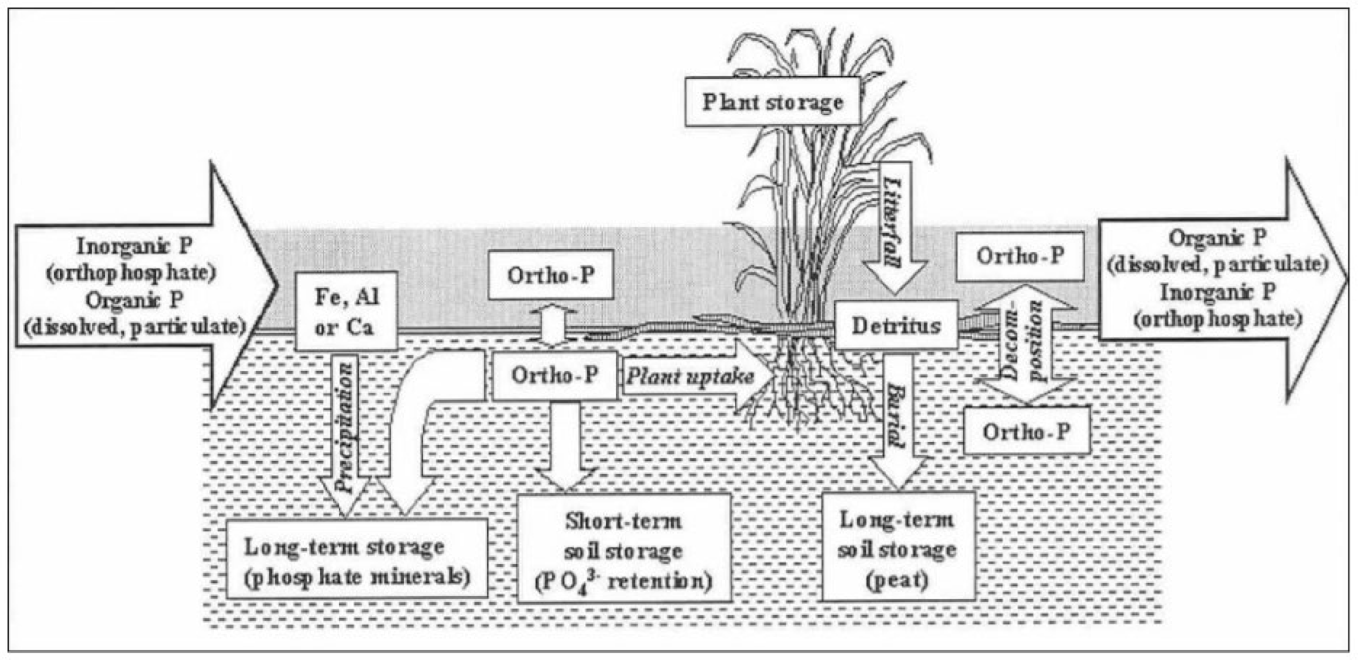


Figure 6: Nitrogen transformations in a constructed wetland treatment system (Cooper *et al.*, 1996)

Plant species	Uptake (kg/ha/year)
Phragmites	750 – 2,450
Scripus	125 - 775
Typha	111 – 2,630

Phosphorus

- Primarily as organic phosphorus and orthophosphate;
- Organic phosphorus is converted to orthophosphate as part of organic matter degradation;
- Chemical precipitation (usually happening in FWS)
- Sedimentation (usually happening in FWS)
- Sorption (Reactive media – materials rich in Ca, Fe and Al) – usually happening in VF and HF
- Plant and microbial uptake



Pathogens

- Physical – filtration and sedimentation
- Chemical – oxidation and adsorption to organic matter
- Biological – oxygen release and bacterial activity in root zone (rhizosphere); aggregation and retention in biofilms; natural die-off; predation and competition for limiting nutrient or trace elements

Advantages

- simple construction (can be constructed with local materials)
- simple O/M,
- low energy maintenance,
- little excess sludge production,
- cost effectiveness (low construction and operation costs),
- increase in biodiversity,
- utilization of the harvested aquatic plants for a variety of purposes (biomass, biogas, animal feed, fertilizer, using stems for thatching, matting, fencing, etc.)

Disadvantages

- large area requirement,
- not appropriate for treating some wastewater with high concentrations of certain pollutants,
- surface flow wetlands can attract mosquitoes and other pests,
- performance of wetlands may vary based on usage and climatic conditions,
- there may be a prolonged initial start-up period before vegetation is adequately established

Design approaches

- HF and FWS CW
  - Loading charts
  - Plug-flow k-C*
  - P-k-C*

- VF and French VF CW
  - Rule of thumb (also used for HF CW)

Rule of thumb

- Based on a particular CW application in a specific climate or geographical region;
- Local or national guideline for a single CW technology

Country	Technology	Specific surface area (m^2/PE)	Reference
Austria	VF	4	ÖNORM B 2505 (2009)
Denmark	HF	5	Brix and Johansen (2004)
	VF	3	
Germany	VF	4	DWA-A 262 (2017)
France	French VF	2	Iwema et al. (2005)

Plug-flow k-C* (first order equation)

$$A = \frac{Q_i}{k_A} \ln\left(\frac{C_o - C^*}{C_i - C^*}\right)$$

where:

C_o = outlet concentration, mg/L

C_i = inlet concentration, mg/L

C^* = background concentration, mg/L

k_A = modified first-order areal rate coefficient, m/d

Q_i = influent flow rate, m^3/d

$$k_T = k_{20}\theta^{(T-20)}$$

where:

k_T = rate coefficient at water temperature T

k_{20} = rate coefficient at water temperature 20°C

T = water temperature, °C

θ = modified Arrhenius temperature factor, dimensionless

Example temperature correction factors (θ-values) for HF and FWS wetlands (50th percentile values, Kadlec and Wallace, 2009).

Parameter	**HF**	**FWS**
BOD_5	0.981	0.985
TN	1.005	1.056
NH_4-N	1.014	1.014
NO_x-N	–	1.102
Thermotolerant coliform	1.002	–

Mass loading charts

- From a collection of 1,500 small-scale wetlands around the world;
- Lines correspond to 50th, 75th and 90th percentile data collected;
- Based on influent mass loading rate, desired effluent concentration and risk tolerance.

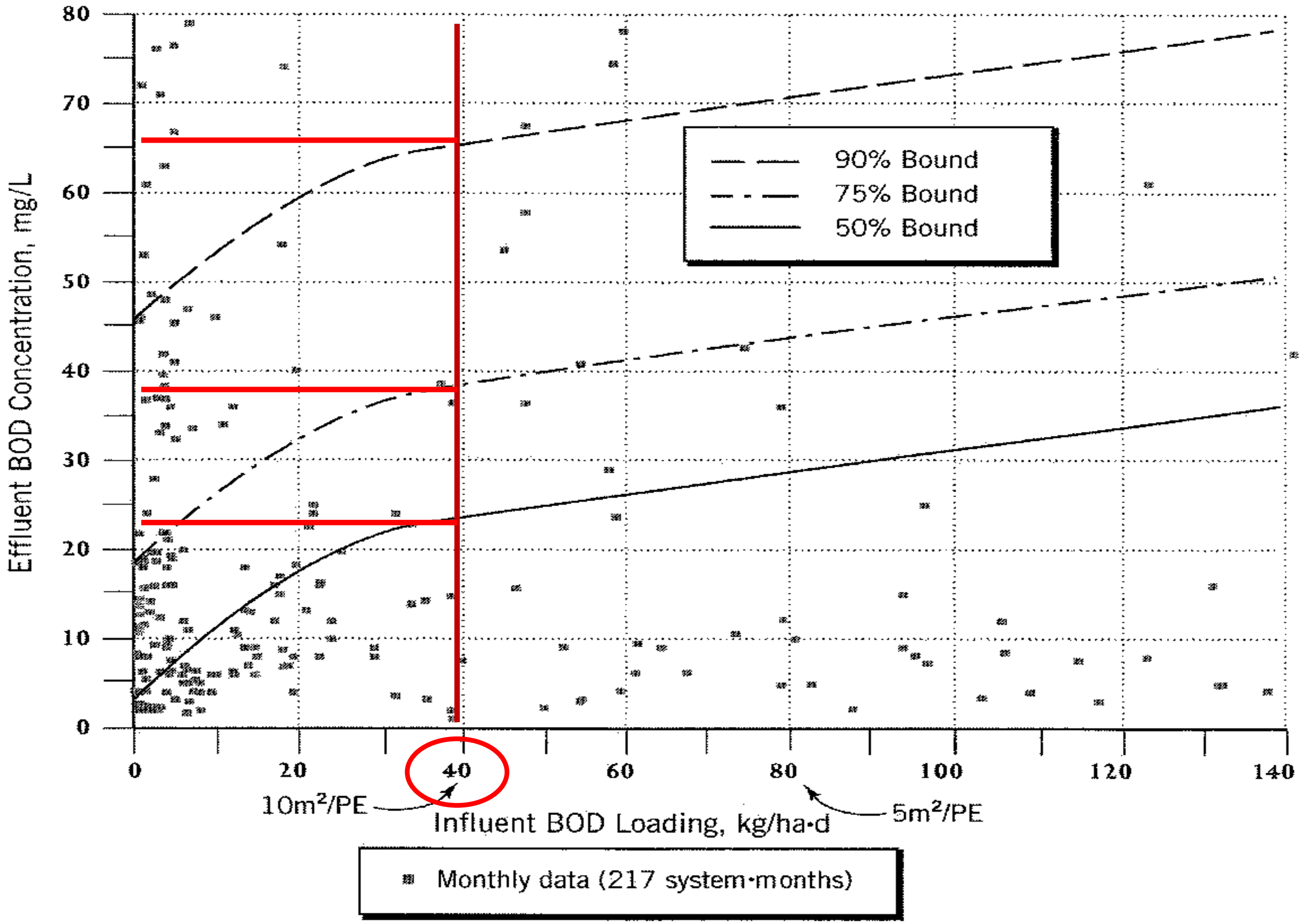


Figure 8-1: VSB Areal Loading Chart for Biochemical Oxygen Demand.

Mass loading charts

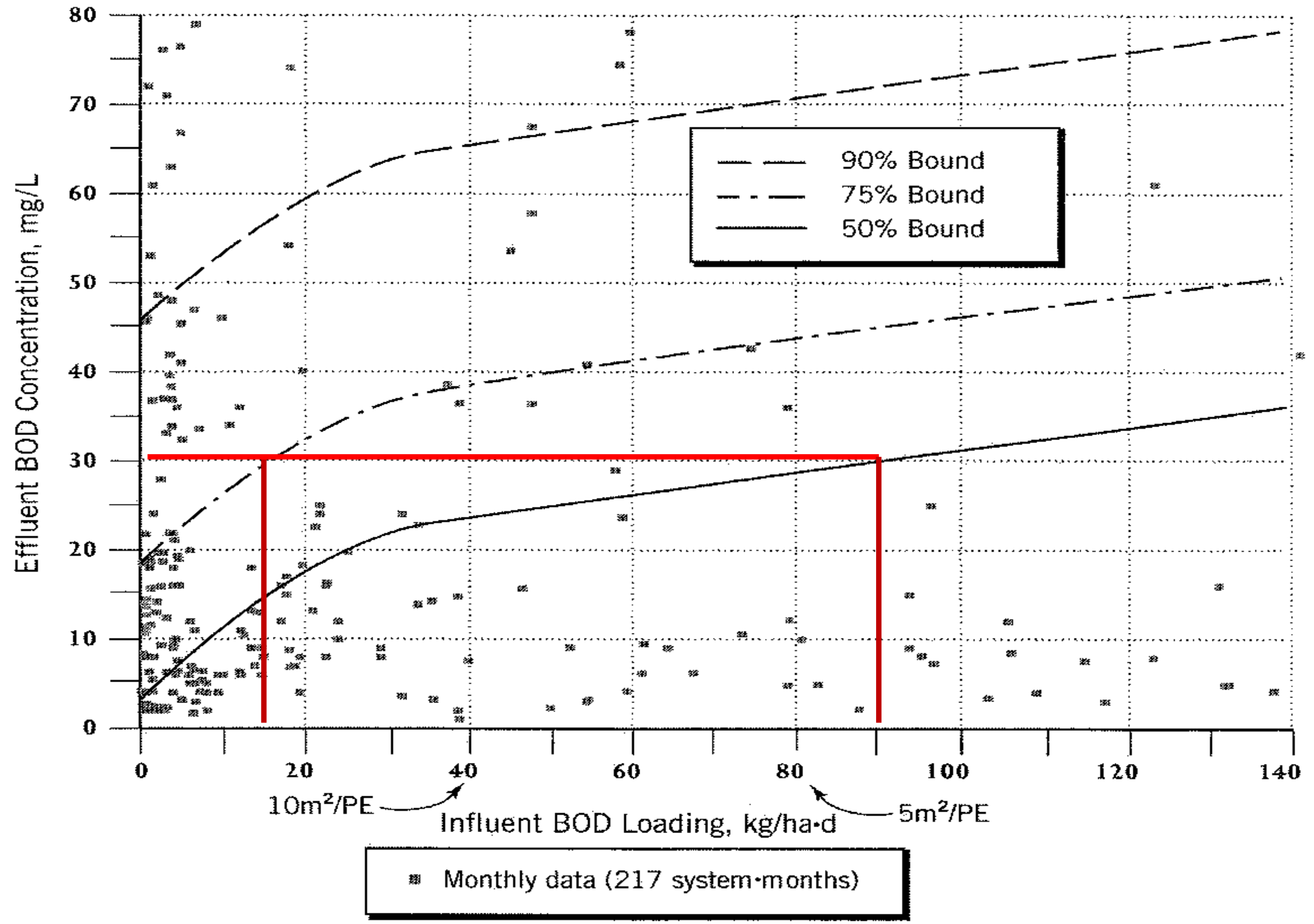


Figure 8-1: VSB Areal Loading Chart for Biochemical Oxygen Demand.

Mass loading chart for FWS

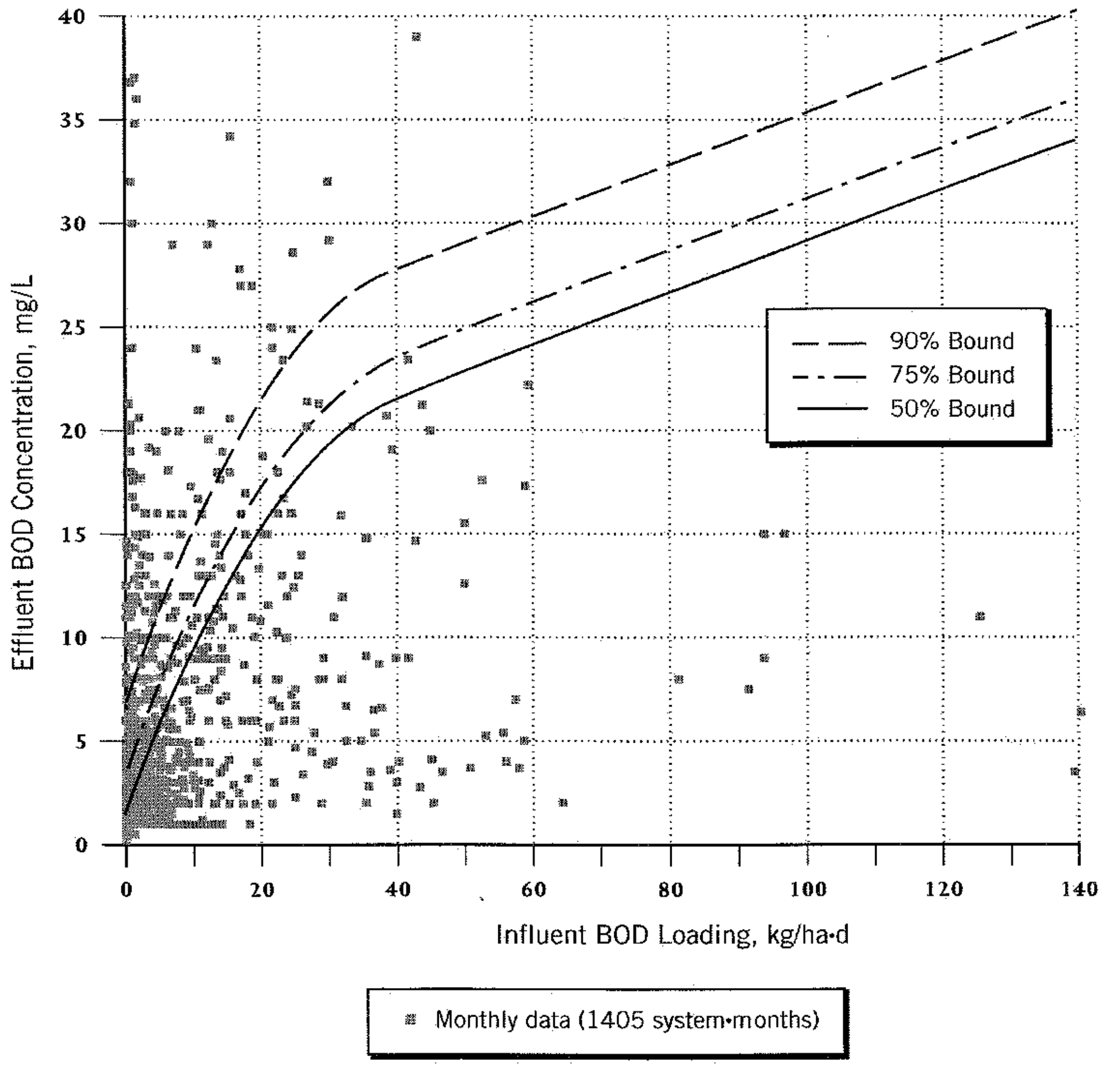


Figure 6-2. FWS Areal Loading Chart for Biochemical Oxygen Demand.

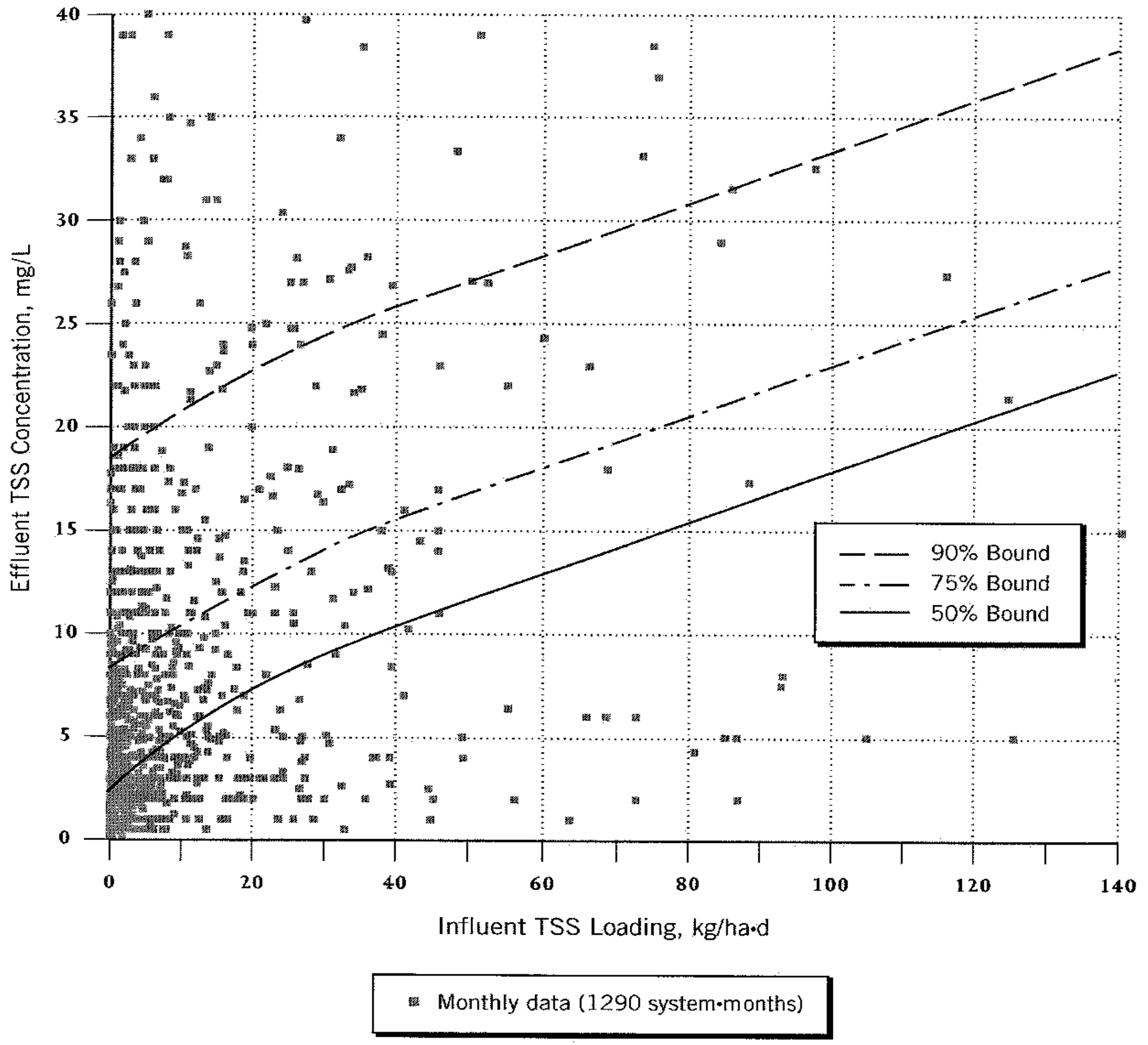


Figure 6-3. FWS Areal Loading Chart for Total Suspended Solids.

Mass loading chart for FWS

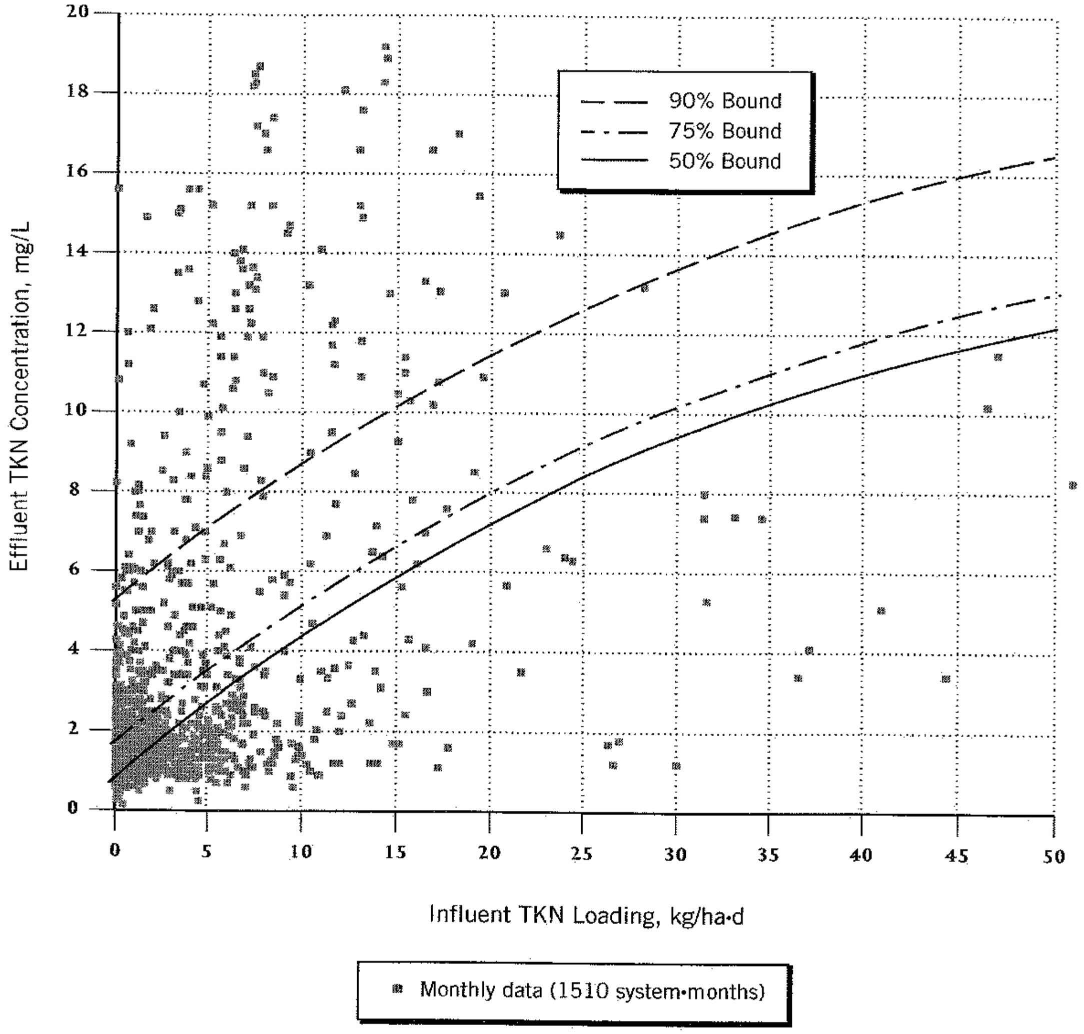


Figure 6-4. FWS Areal Loading Chart for Total Kjeldahl Nitrogen.

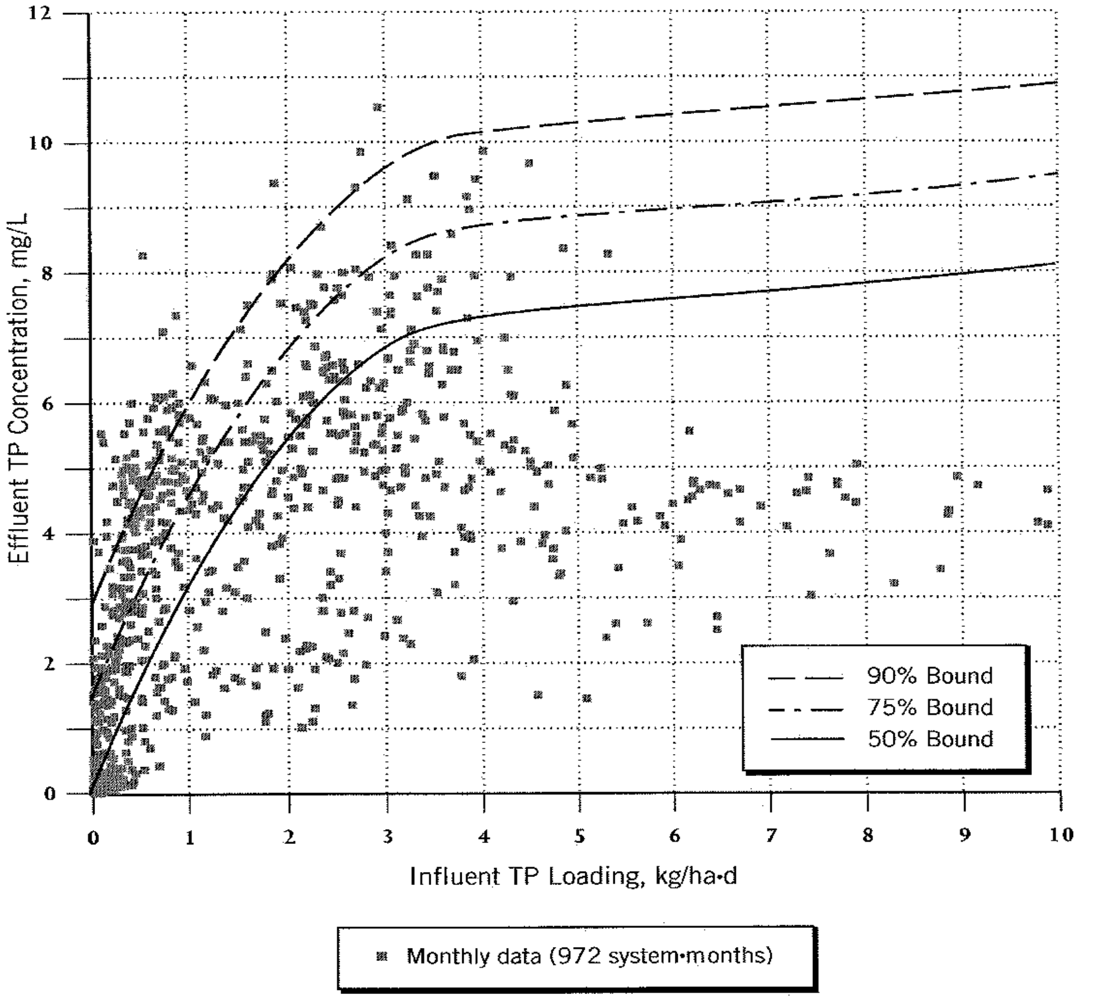
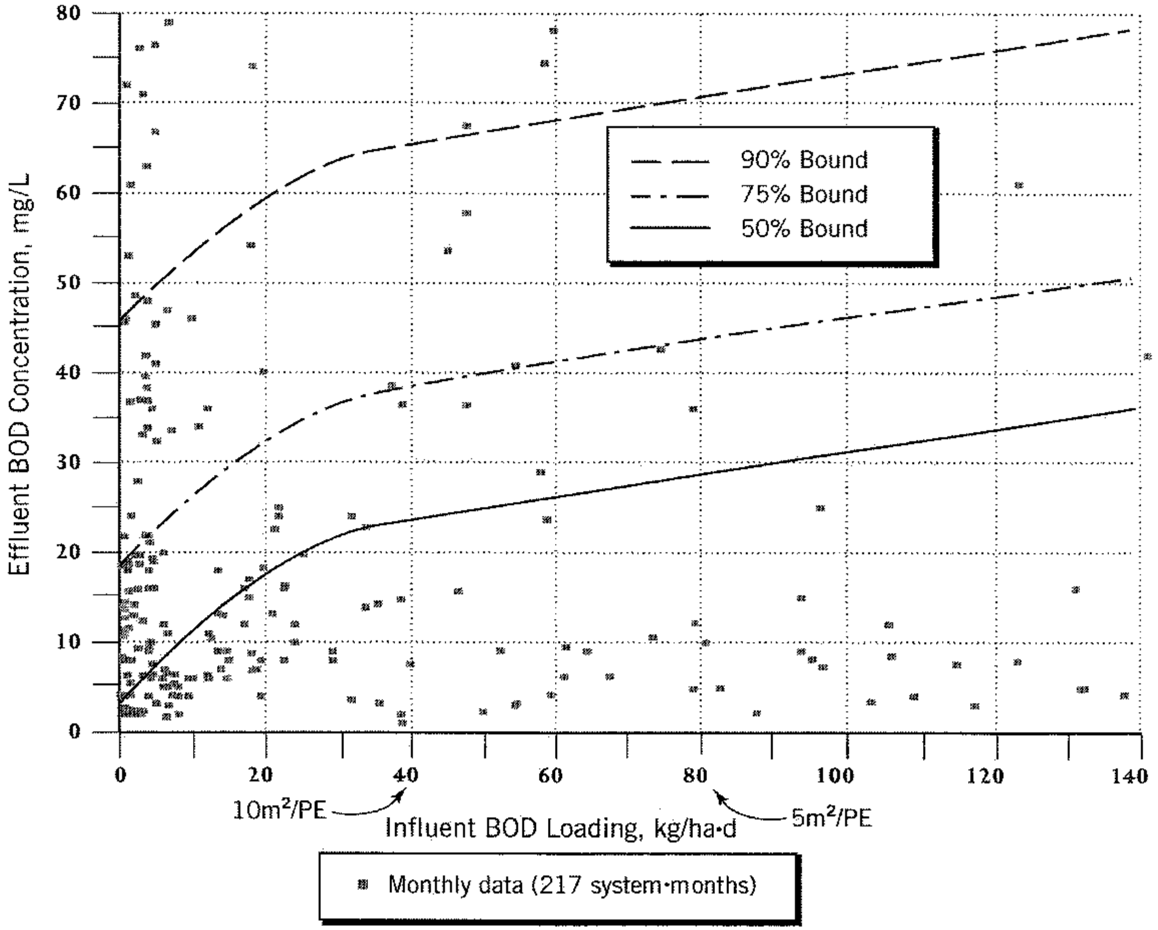


Figure 6-5. FWS Areal Loading Chart for Total Phosphorus.

Mass loading chart for HF CW



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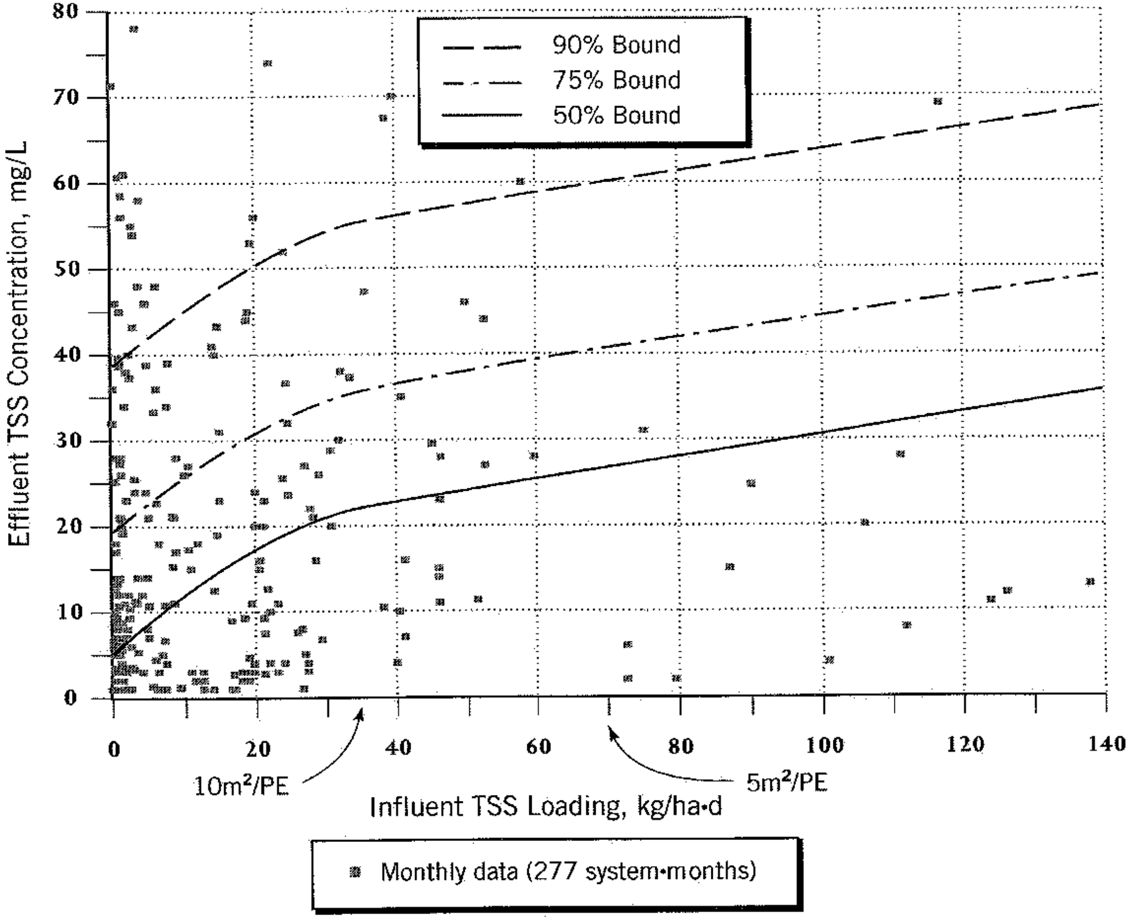


Figure 8-2: VSB Areal Loading Chart for Total Suspended Solids.

Mass loading chart for HF CW

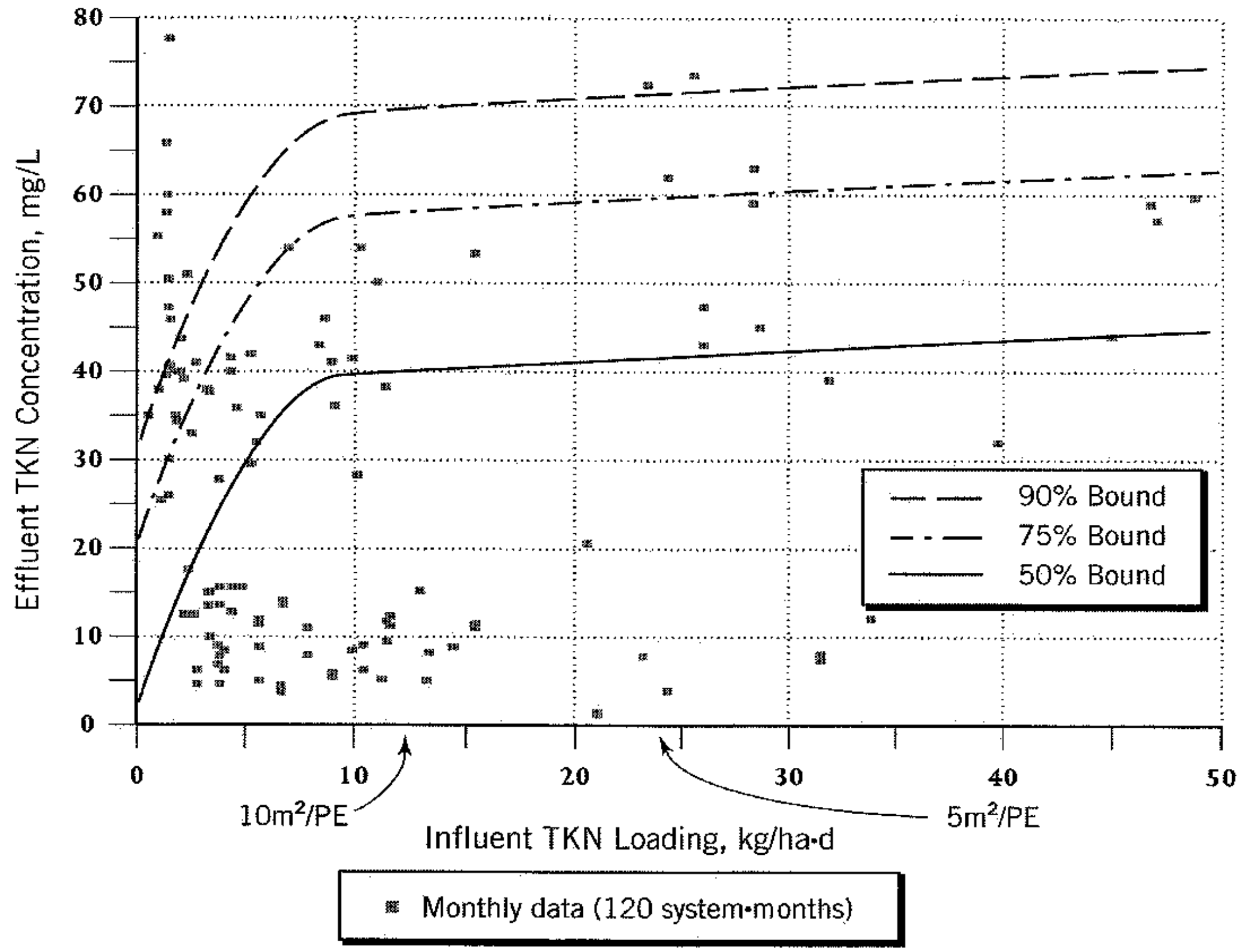


Figure 8-3: VSB Areal Loading Chart for Total Kjeldahl Nitrogen.

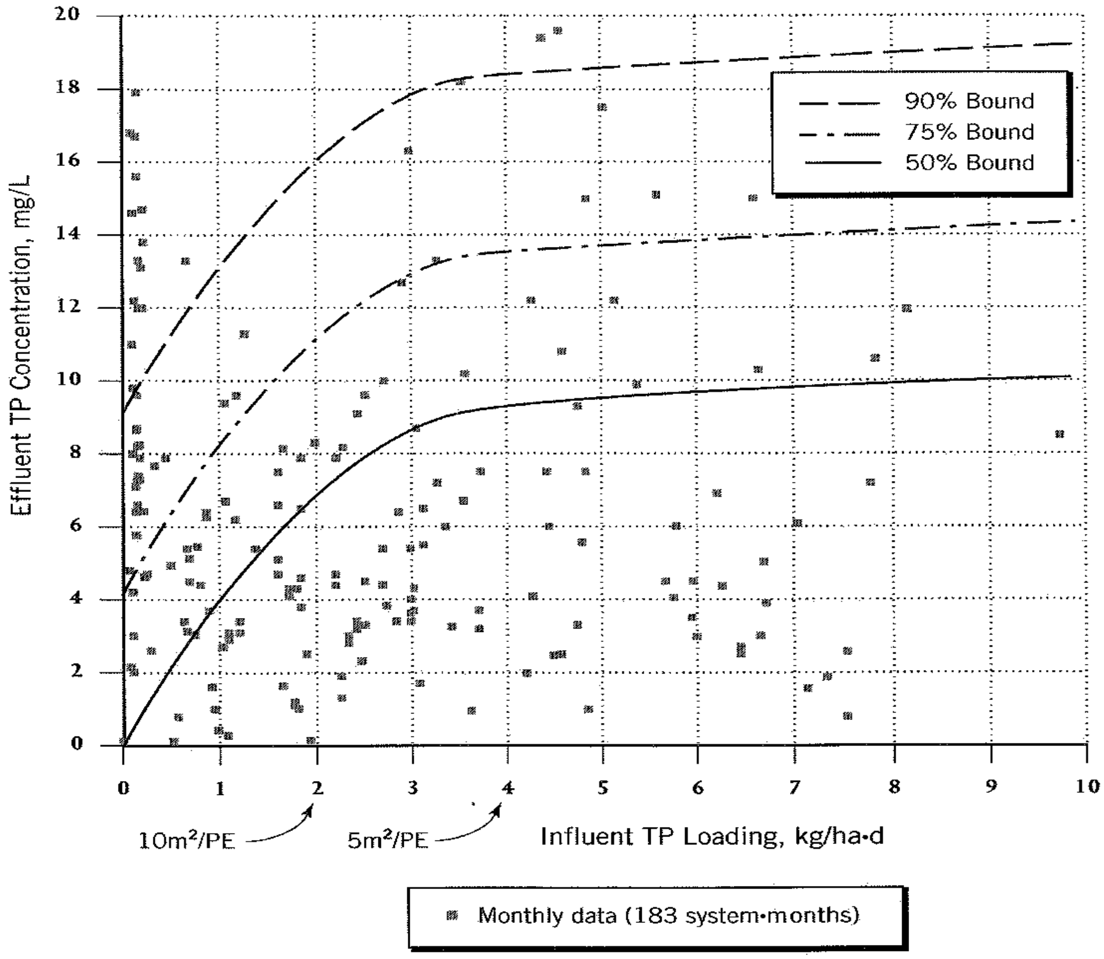


Figure 8-4. VSB Areal Loading Chart for Total Phosphorus.

Modified first order equation P-k-C*

$$A = \frac{PQ_i}{k_A}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right) = \frac{PQ_i}{k_V h}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right)$$

where:

C_o = outlet concentration, mg/L

C_i = inlet concentration, mg/L

C^* = background concentration, mg/L

h = wetland water depth, m

k_A = first-order areal rate coefficient, m/d

k_V = first-order volumetric rate coefficient, 1/d

P = apparent number of tanks-in-series (TIS), dimensionless

Q_i = influent flow rate, m^3/d

Modified first order equation P-k-C*

Examples of *P* values for HF, VF, and FWS wetlands (Kadlec and Wallace, 2009).

Parameter	HF	VF	FWS
BOD_5	3	2	1
TN	6	n.g. [a]	3
NH_4-N	6	6	3

[a] n.g. = not given

Example background concentrations (C^*) in mg/L for HF, VF, and FWS wetlands (Kadlec and Wallace, 2009).

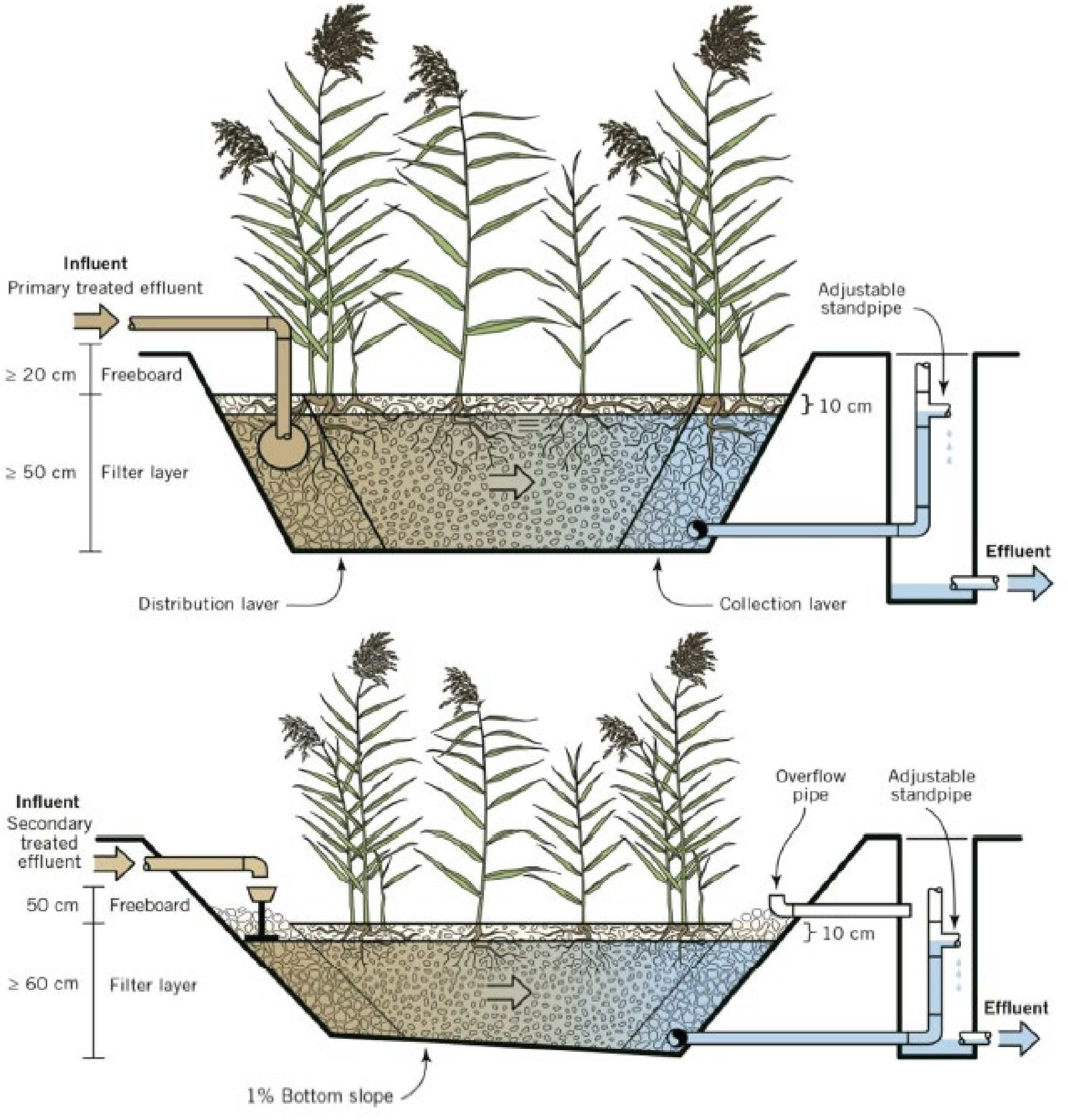
Parameter	HF	VF	FWS	
			Lightly Loaded	Heavily Loaded
BOD_5	10	2	2	10
TN	1	0	1.5	
NH_4-N	0	0	0.1	0.1

Example areal-based reaction rate coefficients (50th percentile) for HF and FWS wetlands (Kadlec and Wallace, 2009).

Pollutant	HF k_A-rate (m/yr)	FWS k_A-rate (m/yr)
BOD_5	25	33
TN	8.4	12.6
NH_4-N	11.4	14.7
NO_x-N	41.8	26.5
Thermotolerant coliform	103	83

Horizontal Flow CW

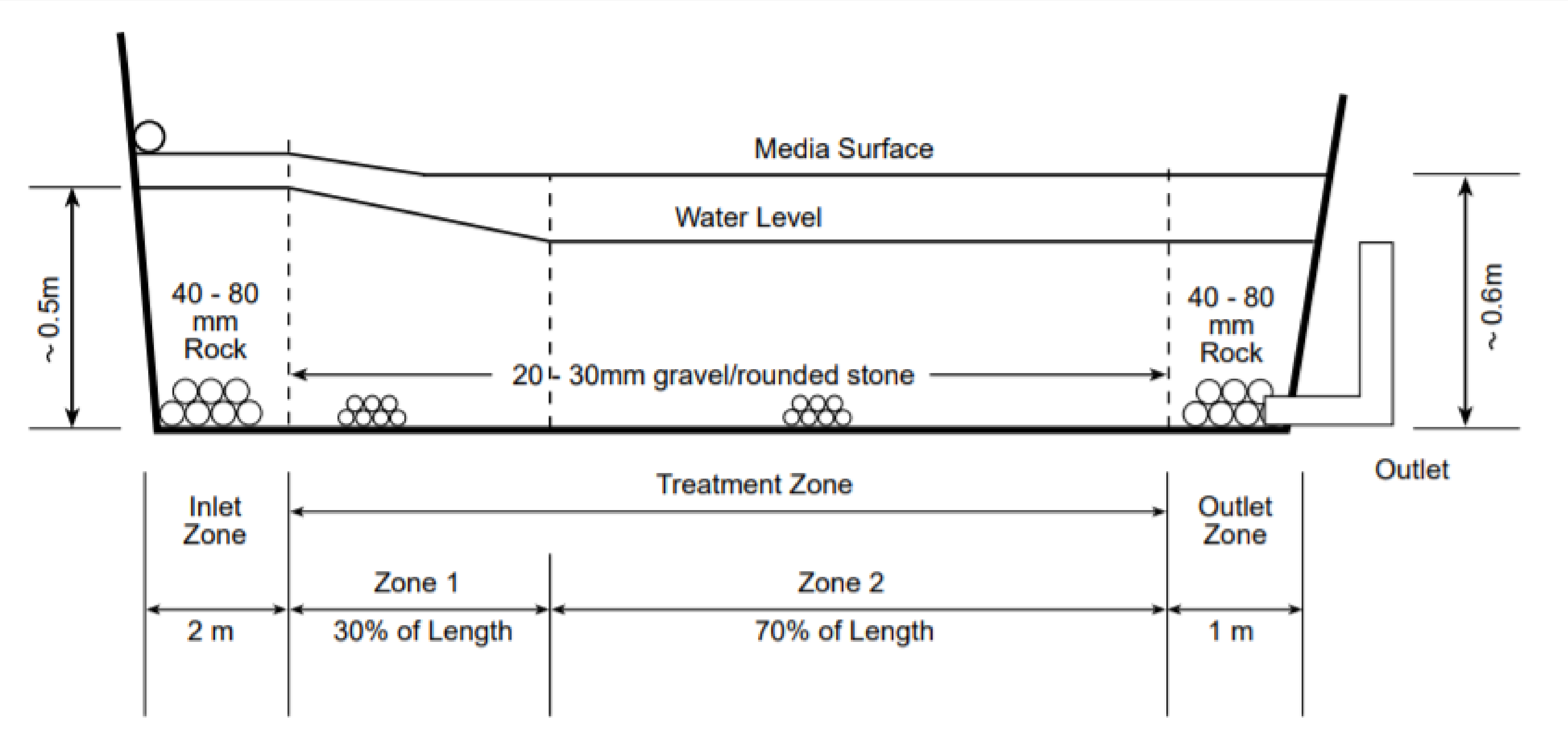
- Used for secondary and tertiary treatment (mostly in the UK);
- Primary treatment is mandatory (e.g. septic tank; ABR);
- Gravel bed is saturated and planted with emergent macrophytes;
- Bed is isolated from the surrounding (e.g. plastic liner; geotextile membrane);
- Gravel depth 0.5 to 0.7 m and water depth is 5-10 cm below the surface;



Typical schematic of a HF wetland; top: secondary treatment; bottom: tertiary treatment of domestic wastewater.

HF CW – Media and depth

- Media and depth of a HF CW as per US-EPA



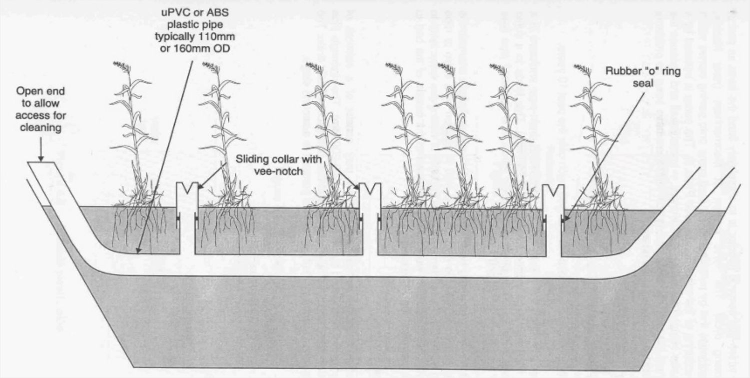
- Most frequently used media size in Europe/UK is 8-16 mm and have been built 0.6 m deep

Inlet (continuous loading)

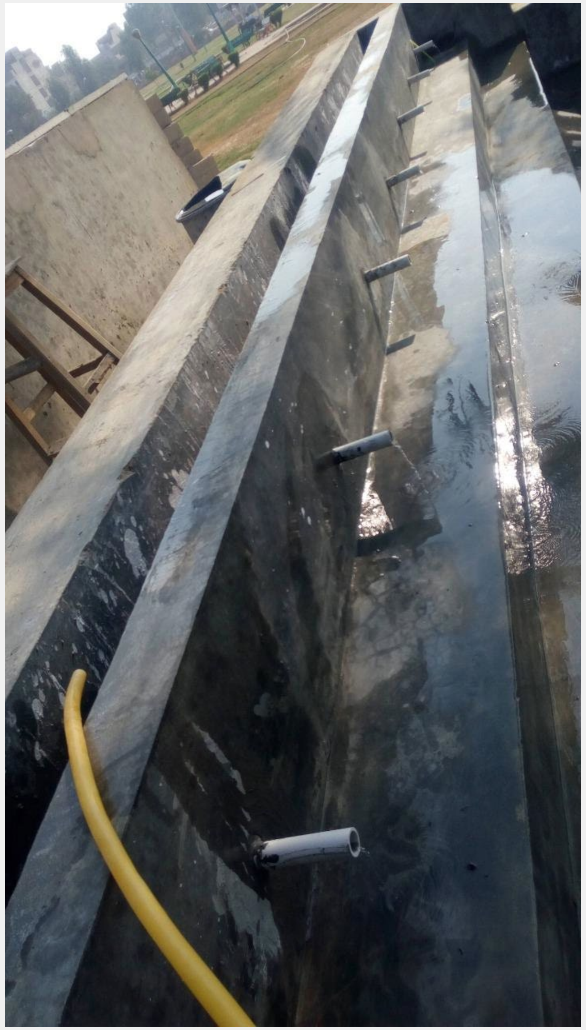
- Pipes (perforated)

- Channels

- Riser pipes with vee-notches

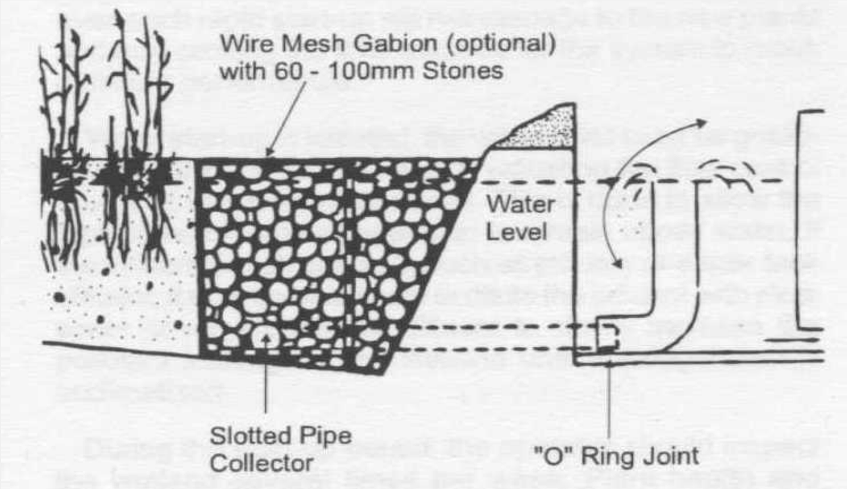


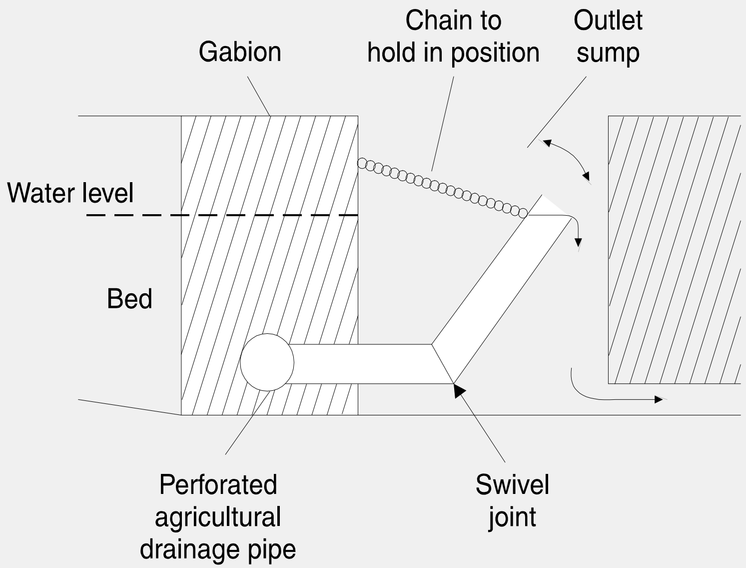
Inlet (continuous loading)



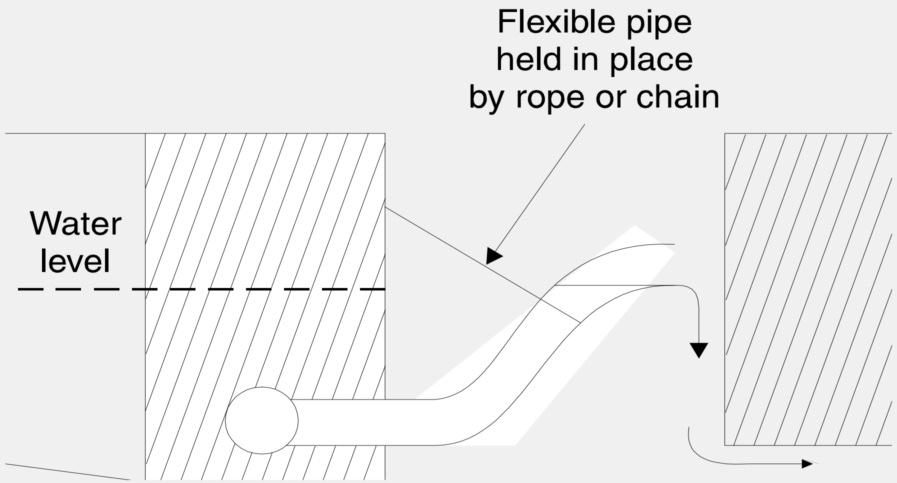
Outlet

- Elbow outlet



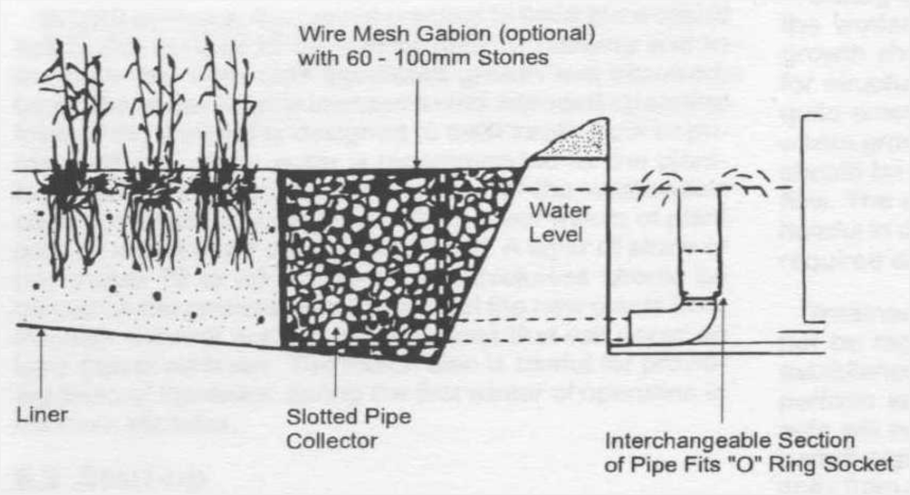


Outlet



- Flexible plastic pipe

- Socketed pipe



Site clearance, earthwork in excavation

Compaction

Construction of wall/basin

Basin ready for lining

Sealing/plastic liner

Filling of substrate

HF CW with plantation

HF CW in operation

Design

Design a HF CW for five households (20PE) for a small community in a temperate climate. The average per capita wastewater generation is 150L/day and BOD_5 load of 60g per person per day (DWA, 2017). The effluent from the HF CW should meet the BOD_5 effluent standard of 30 mg/L.

Assume that a primary treatment precedes the HF CW and reduces the BOD_5 load by 1/3.

Rule of thumb

Country	Technology	Specific surface area (m^2/PE)	Reference
Austria	VF	4	ÖNORM B 2505 (2009)
Denmark	HF	5	Brix and Johansen (2004)
	VF	3	
Germany	VF	4	DWA-A 262 (2017)
France	French VF	2	Iwema et al. (2005)

Area = 5 x 20 = 100 m^2

Plug flow k-C*

$$A = \frac{Q_i}{k_A} \ln \left(\frac{C_o - C^*}{C_i - C^*} \right)$$

where:

C_o = outlet concentration, mg/L

C_i = inlet concentration, mg/L

C^* = background concentration, mg/L

k_A = modified first-order areal rate coefficient, m/d

Q_i = influent flow rate, m^3/d

Example background concentrations (C^*) in mg/L for HF, VF, and FWS wetlands (Kadlec and Wallace, 2009).

Parameter	HF	VF	FWS Lightly Loaded	FWS Heavily Loaded
BOD_5	10	2	2	10
TN	1	0	1.5	
NH_4-N	0	0	0.1	0.1

Calculate Q_i

Average wastewater production = 150 Litres per capita per day

Number of users = 20

Qi = 20 X 150 = 3,000 Litres/day = 3 m^3/day

Calculate C_i

Average BOD_5 production = 60 g per person per day

BOD_5 concentration = (60 x 1,000)/150 = 400 mg/L

BOD_5 removal in primary treatment = 1/3 (33%)

BOD_5 inlet concentration = (2/3) X 400 = 266.66 mg/L

C_o = 30 mg/L

C* (Table)

k_A (Table)

Example areal-based reaction rate coefficients (50th percentile) for HF and FWS wetlands (Kadlec and Wallace, 2009).

Pollutant	HF k_A-rate (m/yr)	FWS k_A-rate (m/yr)
BOD_5	25	33
TN	8.4	12.6
NH_4-N	11.4	14.7
NO_x-N	41.8	26.5
Thermotolerant coliform	103	83

Area = 111.78 m^2

Plug flow k-C* (dimensioning and check for design)

Dimension
Length:Width rate (2:1 to 4:1)

Width of HF CW = 7 (assume)
Length of HF CW = Area/Depth = 111.78/7 = 15.97 m
Check for Length:Width ratio = 2.28:1

Provide length = 16 m
Depth = 0.50 m

Check for cross-sectional organic loading < 250 g BOD_5 / (m^2.d)

Cross-sectional area
= W x D = 7 x 0.5 = 3.5 m^2

BOD_5 load in (M_i)
= BOD_5 concentration x Inflow Q
= 266.7 x 3 = 800 g BOD_5 /d

Cross-sectional organic loading rate
= M_i /Cross-sectional area
= 800 / 3.5 = 228.57 g BOD_5 / (m^2.d)

Modified Plug flow P-k-C*

$$A = \frac{PQ_i}{k_A}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right) = \frac{PQ_i}{k_V h}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right)$$

where:

C_o = outlet concentration, mg/L

C_i = inlet concentration, mg/L

C^* = background concentration, mg/L

h = wetland water depth, m

k_A = first-order areal rate coefficient, m/d

k_V = first-order volumetric rate coefficient, 1/d

P = apparent number of tanks-in-series (TIS), dimensionless

Q_i = influent flow rate, m^3/d

Q_i = 3 m^3/day

C_i = 266.66 mg/L

C^* = 10 mg/L

C_o = 30 mg/L

k_A = 25 m/yr = 0.068 m/d

P (From table)

Examples of P values for HF, VF, and FWS wetlands (Kadlec and Wallace, 2009).

Parameter	HF	VF	FWS
BOD_5	3	2	1
TN	6	n.g. [a]	3
NH_4-N	6	6	3

[a] n.g. = not given

Area = 176.24 m^2

Modified Plug flow k-C* (dimensioning and check for design)

Dimension
Length:Width rate (2:1 to 4:1)

Width of HF CW = 9 (assume)
Length of HF CW = Area/Depth = 176.24/9 = 19.58 m
Check for Length:Width ratio = 2.18:1

Provide length = 20 m
Depth = 0.50 m

Check for cross-sectional organic loading < 250 g BOD_5 / (m^2.d)

Cross-sectional area
= W x D = 9 x 0.5 = 4.5 m^2

BOD_5 load in (M_i)
= BOD_5 concentration x Inflow Q
= 266.7 x 3 = 800 g BOD_5 /d

Cross-sectional organic loading rate
= M_i /Cross-sectional area
= 800 / 4.5 = 177.78 g BOD_5 / (m^2.d)

Mass Loading chart

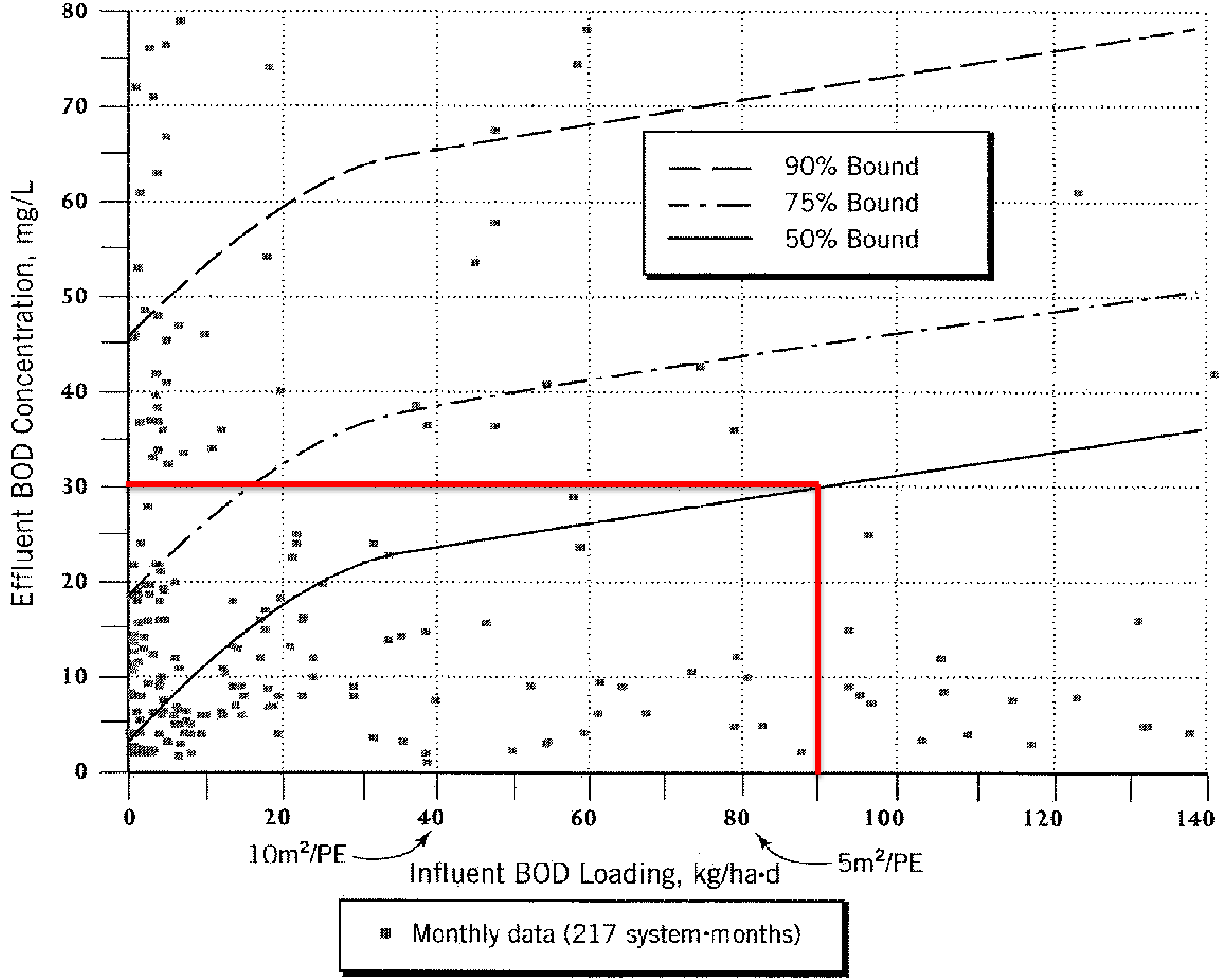


Figure 8-1: VSB Areal Loading Chart for Biochemical Oxygen Demand.

BOD_5 load in (M_i)
= 800 g BOD_5 /d

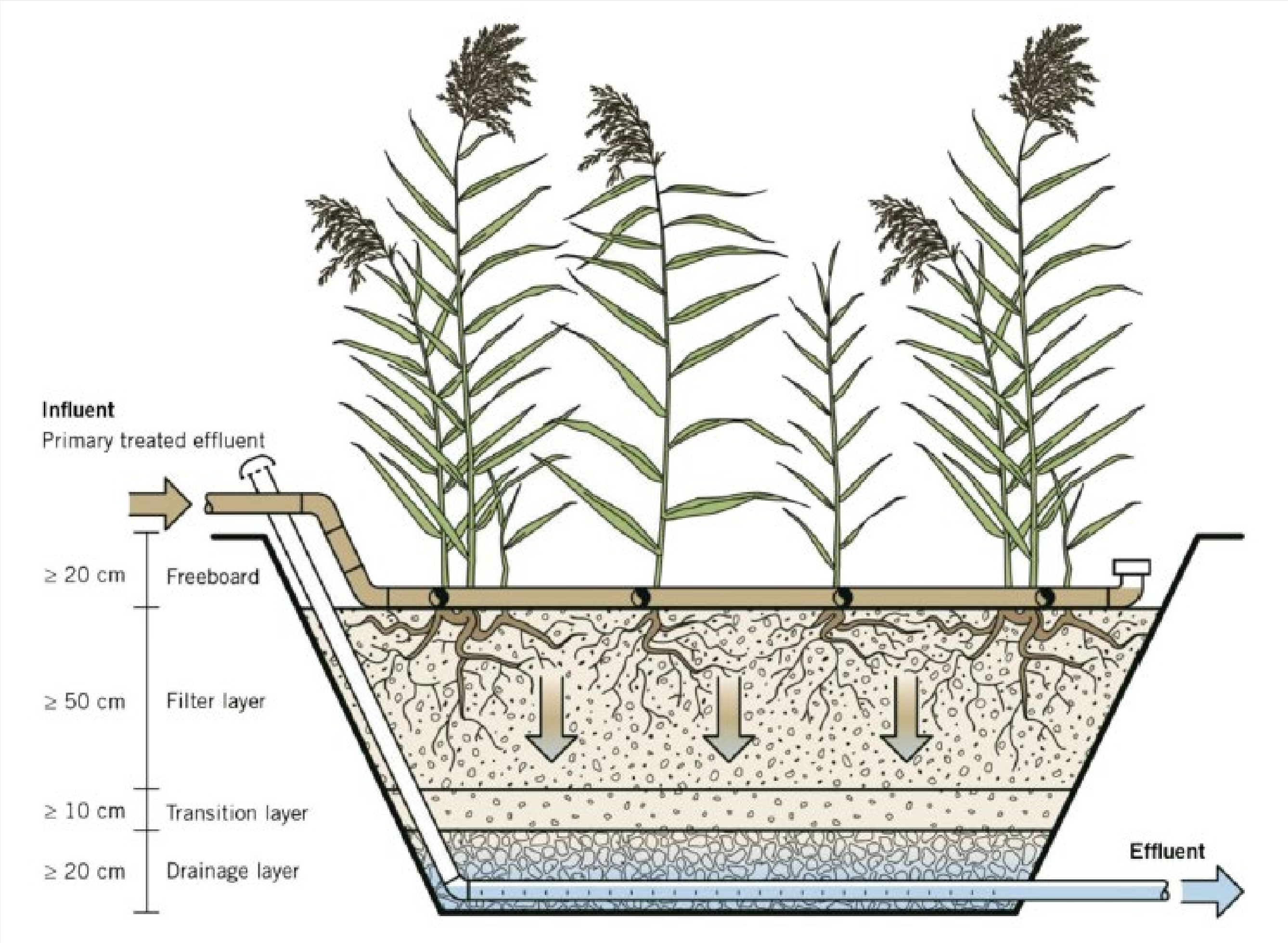
Choose confidence interval – 50%
Effluent BOD_5 concentration = 30 mg/L

Influent BOD_5 loading rate
= 90 kg/ha-d
= 9 g/m^2-d

Area = 800/9 = 88.89 m^2

Vertical Flow CW

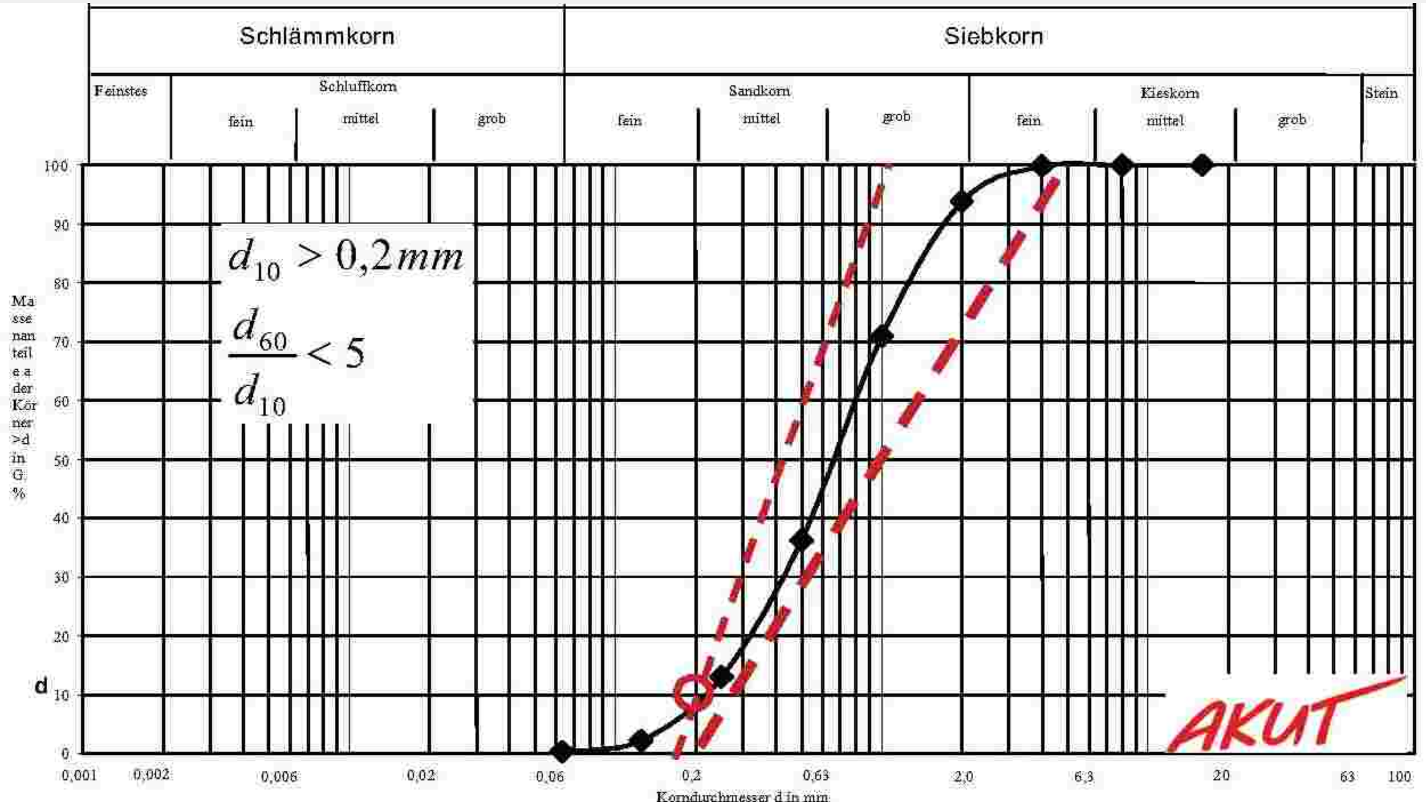
- Secondary or tertiary wastewater treatment;
- Sand and/or gravel bed is planted with emergent macrophytes;
- Primary treated wastewater is loaded intermittently;
- Bed is isolated from the surrounding (e.g. plastic liner; geotextile membrane);
- Efficient for removal of organics and aerobic processes like nitrification;



VF CW: Media & depth

- Media
  - Effective grain size (d_{10}) > 0.2 mm
  - Uniformity coefficient (d_{60}/d_{10}) < 5

Design Parameter	Denmark [a]	Germany	Austria
Main layer			
Filter material	Sand	Sand 0.06 – 2 mm	Sand 0.06 – 4 mm
Depth (cm)	100	> 50	> 50
d_{10} (mm)	0.25 – 1.2	0.2 – 0.4	0.2 – 0.4
d_{60} (mm)	1 – 4	-	-
$U = d_{60}/d_{10}$	< 3.5	< 5	-



transition layer (10 cm) - 4/8 mm
drainage layer (20 cm) - 16/32 mm

Inlet (intermittent loading)


Outlet

- collection system of a network of perforated pipes surrounded by large stones at the bottom.

Substrate (main layer) filling in VF CW

Substrate (protection layer) filling in VF CW

Completed VF CW

Distribution network (intermittent loading)

VF CW in operation

Design

Design a VF CW for five households (20PE) for a small community in a temperate climate. The average per capita wastewater generation is 150L/day and BOD_5 load of 60g per person per day (DWA, 2017). The effluent from the VF CW should meet the BOD_5 effluent standard of 30 mg/L.

Assume that a primary treatment precedes the VF CW and reduces the BOD_5 load by 1/3.

Rule of thumb

Country	Technology	Specific surface area (m^2/PE)	Reference
Austria	VF	4	ÖNORM B 2505 (2009)
Denmark	HF	5	Brix and Johansen (2004)
	VF	3	
Germany	VF	4	DWA-A 262 (2017)
France	French VF	2	Iwema et al. (2005)

Area = 4 x 20 = 80 m^2

Modified Plug flow P-k-C* (k_A – Cairo)

Table 6 The effect of different operational conditions of constructed wetland on the areal removal rate (k_A) and volumetric removal rate (k_V) of COD, BOD, TSS, NH_4 and TP.

Vegetation	Media type	COD	BOD	TSS	NH_4	TP
k_V (d^{-1})						
Planted beds	Gravel	2.64[a]	3.68[a]	2.59[b]	0.66[b]	0.40[b]
	Vermiculite	2.95[a]	3.85[a]	3.27[a]	0.96[a]	0.66[a]
Unplanted beds	Gravel	0.76[a]	0.98[a]	1.04[a]	0.52[a]	0.24[b]
	Vermiculite	0.57[b]	0.86[a]	1.15[a]	0.73[a]	0.50[a]
k_A ($m\ d^{-1}$)						
Planted beds	Gravel	0.20	0.27	0.19	0.05	0.03
	Vermiculite	0.22	0.29	0.24	0.07	0.05
Unplanted beds	Gravel	0.06	0.07	0.08	0.04	0.02
	Vermiculite	0.04	0.06	0.09	0.05	0.04

Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

Modified Plug flow P-k-C*

$$A = \frac{PQ_i}{k_A}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right) = \frac{PQ_i}{k_V h}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right)$$

where:

C_o = outlet concentration, mg/L

C_i = inlet concentration, mg/L

C^* = background concentration, mg/L

h = wetland water depth, m

k_A = first-order areal rate coefficient, m/d

k_V = first-order volumetric rate coefficient, 1/d

P = apparent number of tanks-in-series (TIS), dimensionless

Q_i = influent flow rate, m^3/d

Q_i = 3 m^3/day

C_i = 266.66 mg/L

C^* = 10 mg/L

C_o = 30 mg/L

k_A = 0.2 m/d

P (From table)

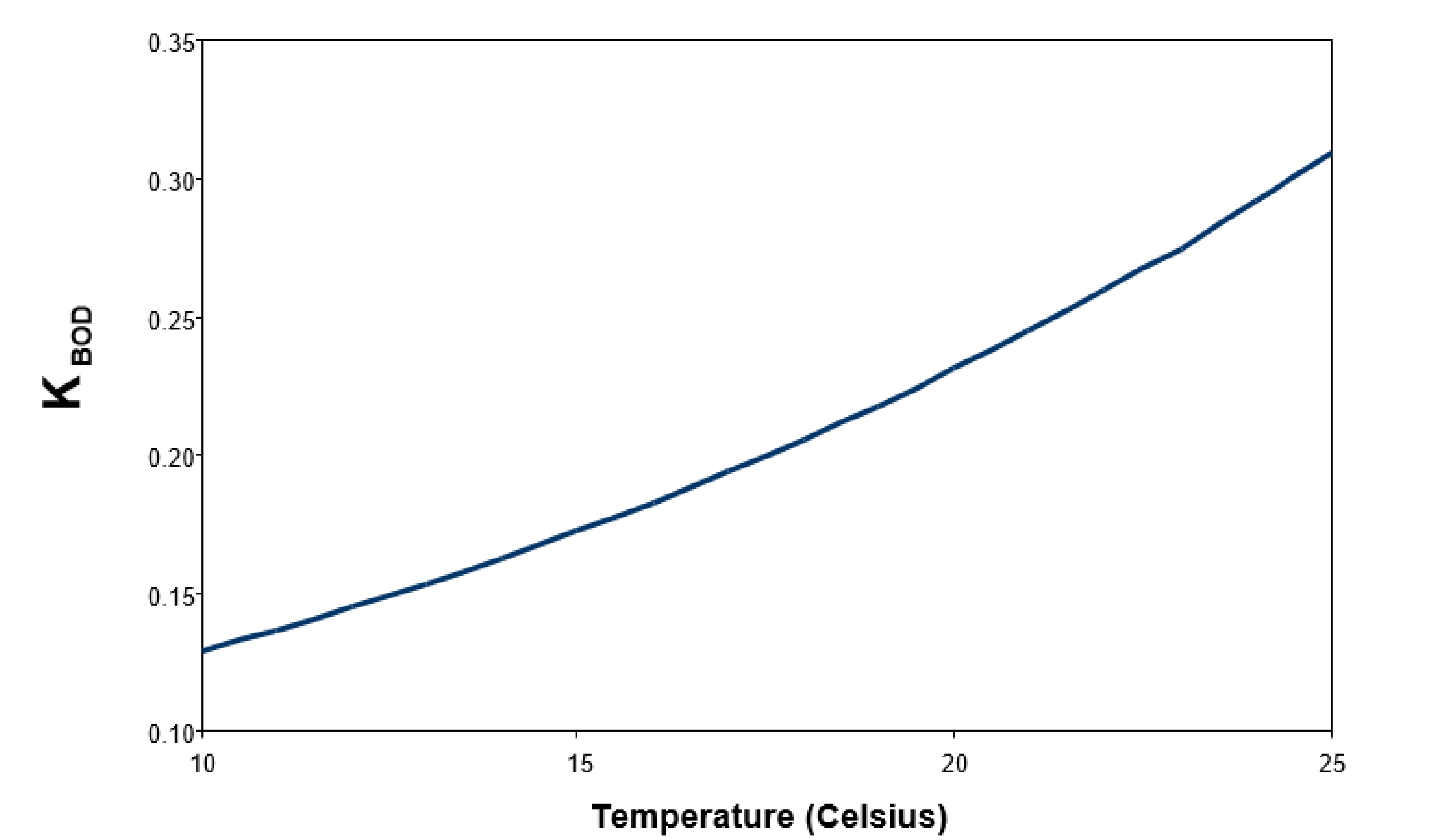
Examples of *P* values for HF, VF, and FWS wetlands (Kadlec and Wallace, 2009).

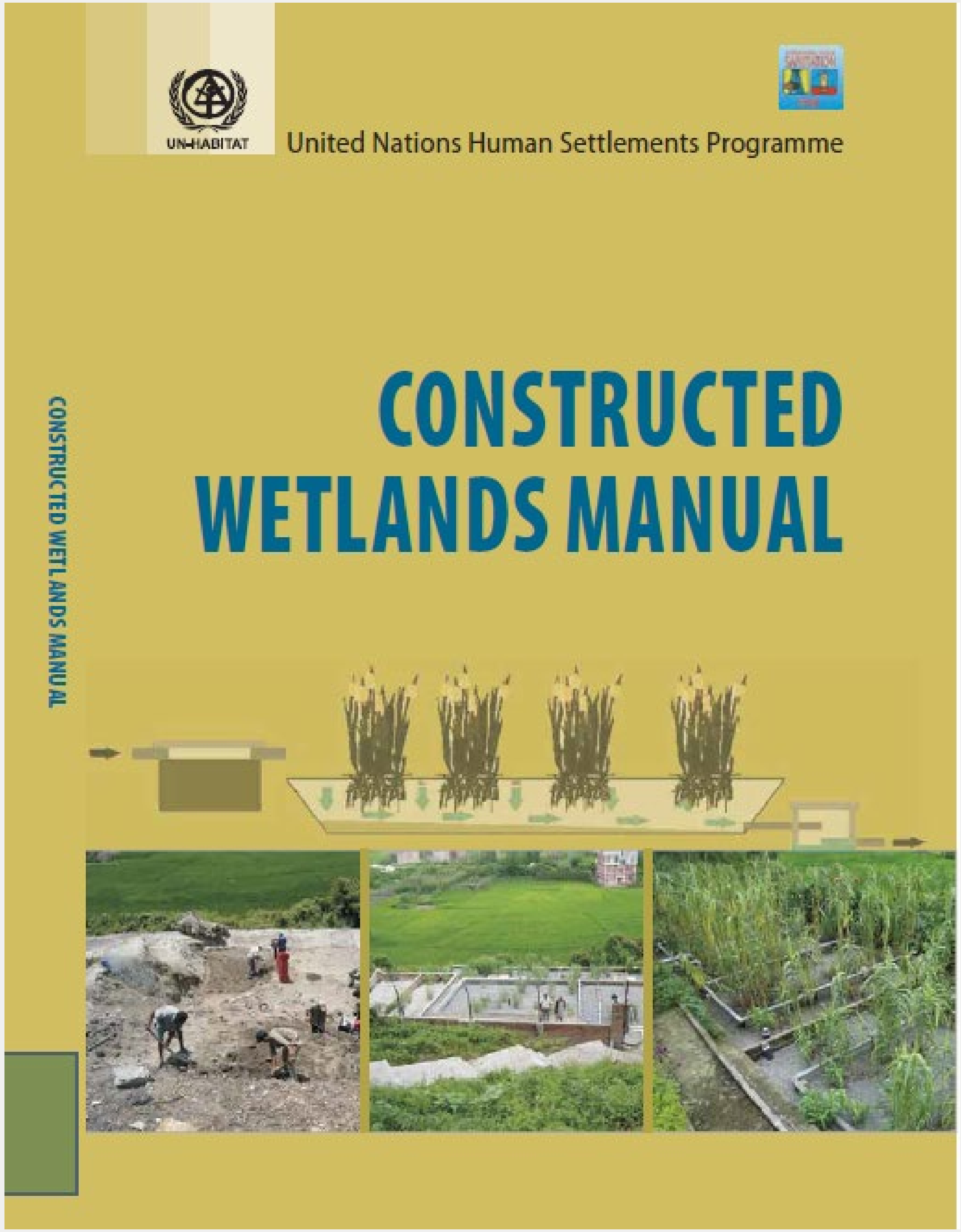
Parameter	HF	VF	FWS
BOD_5	3	2	1
TN	6	n.g. [a]	3
NH_4-N	6	6	3

[a] n.g. = not given

Area = 77.47 m^2

Modified Plug flow P-k-C* (k_{BOD})

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Thank You!

Any Queries?

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